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A Study of the Role of Clouds in the Relationship Between Land Use/Land Cover and the Climate and Air Quality of the Atlanta Area

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Abstract

The goal of Project ATLANTA is to derive a better scientific understanding of how land cover changes associated with urbanization affect climate and air quality. In this project the role that clouds play in this relationship was studied. Through GOES satellite observations and RAMS modeling of the Atlanta area, we found that in Atlanta (1) clouds are more frequent than in the surrounding rural areas; (2) clouds cool the surface by shading and thus tend to counteract the warming effect of urbanization; (3) clouds reflect sunlight, which might otherwise be used to produce ozone; and (4) clouds decrease biogenic emission of ozone precursors, and they probably decrease ozone concentration. We also found that mesoscale modeling of clouds, especially of small, summertime clouds, needs to be improved and that coupled mesoscale and air quality models are needed to completely understand the mediating role that clouds play in the relationship between land use/land cover change and the climate and air quality of Atlanta. It is strongly recommended that more cities be studied to strengthen and extend these results.

1 Introduction

The key goal of Project ATLANTA (ATlanta Land use ANalysis: Temperature and Air quality) is “to derive a better scientific understanding of how land cover changes associated with urbanization, principally in transforming forest lands to urban land covers through time, has, and will, effect local and regional climate, surface energy flux, and air quality characteristics.”¹ Clouds are probably the least known factor in urban climate and air quality. Alteration of land use or land cover has an effect on the atmosphere; the so-called “urban heat island” is one such example. Changes in land use/cover can also result in a change in cloud formation and dissipation, especially in small cumulus clouds. These small clouds shade the surface lowering the surface temperature. This shading may also lessen the formation of photochemical smog. But, since the surface–atmosphere system is interconnected and highly nonlinear, the role of clouds in the relationship between land use/cover and urban climate and air quality is largely unknown. The goal of this research is to understand the role of clouds in this relationship.

We proposed three tasks to build this understanding for the city of Atlanta:

1. Use GOES 8 data to construct a cloud climatology over Atlanta for the summer of 1996. This will serve as a basis for the mesoscale modeling study of clouds described in Task 3.
2. Use GOES 8 data to understand the diurnal variability of albedo, soil moisture availability, thermal inertia, and surface roughness needed to initialize the mesoscale models.
3. Run the RAMS model to simulate the cloud field which is prevalent around Atlanta in the summer. Compare the clouds produced in the model with the clouds deduced from GOES 8 data. Determine what effects changes in land use/land cover would have on the modeled cloud field.

The remainder of this report describes how we completed these tasks and the results that we found.

2 Accomplishments and Results

This project was proposed as a three-year effort. The work for years 1 and 2 was accomplished in a total of 24 calendar months. Two no-cost extensions were granted. The work completed in “Year 3” was actually accomplished between the end of Year 2 and the end of the grant period.

2.1 Year 1 Accomplishments and Results

The work on this project can be divided into two parts: satellite observations of clouds and mesoscale modeling of clouds. The accomplishments and results of these two parts are presented in the next two sections.

¹ Project ATLANTA Proposal, 1996.

2.1.1 Satellite Observations of Clouds

Clouds are one of the key factors in the climate system because of their radiative properties. They reflect incoming shortwave radiation, decreasing the surface temperature; on the other hand, clouds contribute to downward infrared radiation reducing the cooling rate at the surface. Yet there is surprisingly little good data on clouds or their effects. One of the key goals of this project is to collect reliable cloud observations for the Atlanta area.

2.1.1.1 Satellite Data Collection

The first step in this process is to collect high resolution GOES 8 data. The two-month period 5 July 1996 through 5 September 1996 was chosen for study in part because the Atlanta Olympics offered the opportunity to acquire many special weather observations. More than 25,000 GOES 8 images were acquired from the CSU Earthstation and archived on Exabyte tape. The 1 km visible data were transferred to two CD-ROMs for further processing. A third CD-ROM containing the 11 μm (channel 4) data was also made.

In addition, GOES 8 data were collected in May 1997 and in August 1997 at the same time as aircraft observations of Atlanta. Also, GOES data were collected in July and August 1997 to support air quality modeling being done by Haider Taha.

2.1.1.2 Cloud Climatology

A major goal of the CIRA part of Project ATLANTA is the production of a climatology of clouds in the Atlanta area, particularly during the summer. Significant progress toward this goal was made in Year 1 of the project.

2.1.1.2.1 Video Tape

Using the 1996 GOES data, a video tape of the daytime clouds for the entire 63-day period was made. It shows that there were no days in this period which were entirely cloud free. The clearest days had extensive small cumulus coverage which peaked in the early afternoon near the time of peak solar heating. Figure 1 shows a typical day with this type of cumulus cover.

2.1.1.2.2 Cloud Classification

The video tape showed that Atlanta experiences many types of clouds in the summer: thunderstorms, frontal clouds, fog, and small cumulus. A second step toward the cloud climatology was in using the visible imagery to classify each day of the 63-day period into various cloud categories. The most important classification is whether it was clear in the morning or cloudy in the morning. In the afternoon, days which are clear in the morning look like Figure 1, that is, they are dominated by small cumulus clouds, which shade the surface, thus cooling it and possibly reducing the production of photochemical smog. Sixteen days of the 63-day period (about 25%) fell into this category.

2.1.1.2.3 Cloud Cover Algorithm

A final step taken in Year 1 toward constructing a cloud climatology was in formulating an experimental cloud cover algorithm for two days, 21 and 23 August 1996. These days were both clear in the morning and cloudy in the afternoon. Both were chosen for numerical

simulation (see Section 2.1.2). First, the GOES visible channel measurements were converted into isotropic albedo by dividing the reflectances (calibrated according to Weinreb et al., 1997) by the cosine of the solar zenith angle. Next, a histogram of the albedos in the study around Atlanta was constructed each hour. Binning the data in 1% albedo bins, the spread of the clear spots was estimated as the distance from the peak of the distribution to the darkest pixel. It was assumed that the distribution for clear pixels would extend as far on the bright side of the distribution as on the dark side. Any pixels brighter than the assumed clear-sky maximum brightness were classified as cloudy. This scheme worked well for the morning and late afternoon images which appeared to be clear. It also gave reasonable cloud fractions during the cloudy part of the day. (Figure 2).

2.1.1.3 Comparison with Ozone

To investigate what is important in the relationship between clouds and air quality, ozone concentration was selected as a variable to represent air quality. Hourly ozone concentrations, measured at the six air monitoring stations in the Atlanta area were acquired from the Georgia Department of Natural Resources for the 63-day period for which GOES data were collected. Ozone concentration was compared with cloud data in two ways.

2.1.1.3.1 Ozone and cloud type classification

Figure 3 shows the maximum hourly ozone concentration from the six Atlanta monitoring stations for each of the 63 days. The days which were clear in the morning are white, shaded bars indicate days which were cloudy in the morning. Clear mornings tend to be higher ozone days.

2.1.1.3.2 Ozone, Cloud, Solar Insolation Phasing

Ozone is produced by photochemical processes, but is destroyed by other processes. Figure 4 shows that the rise of ozone concentrations is in phase with solar insolation and also with cumulus cloud formation, but ozone persists after the insolation and the clouds decay.

2.1.2 Mesoscale Modeling of Clouds

The effect of urbanization on local climate and weather has been known since 1833 when Howard (1833) published his observations of temperature contrast between London and nearby rural areas. Probably the best known urban effect is the urban heat island which is a temperature excess in a city as compared to its surroundings. Most of the studies on the urban heat island effect were conducted for clear-sky conditions, which are favorable for the urban heat island development. The effect of clouds on a small scale is probably better known qualitatively than quantitatively, and the magnitude of the cloud effect is not well understood. Clouds tend to reduce the diurnal temperature range and, thus, the urban heat island magnitude mainly at night (Kidder and Essenwanger, 1995). Land use alteration can induce changes in cloud development. Warmer and moister surfaces increase the upward moisture flux, resulting in more or larger clouds. The other significant factor in cloud formation is concentration of cloud condensation nuclei (CCN), which is usually higher over urban or industrialized areas (Landsberg, 1981). Thus, urbanization will affect the clouds, which will have an impact on other variables.

The understanding of the role of clouds over a small area like a city has implications in air quality modeling, since these models do not consider clouds. In some cases (like southern California) this is not a deficiency. However, it is a major drawback in humid and cloudy areas such as the Southeast in summer. The magnitude of the cloud effect can provide an estimate of errors in the air quality model.

2.1.2.1 Numerical modeling

RAMS (Regional Atmospheric Modeling System, Pielke et al., 1992) is a numerical model designed for atmospheric applications providing a large degree of flexibility, including hydrostatic or nonhydrostatic options, full microphysics, nested grid capability or 4-D data assimilation. The possible applications can range from hemispheric simulations to modeling of individual storm cells or even to flow over buildings (Nicholls et al., 1995). The major advantage of RAMS relevant to this study is that it explicitly resolves clouds.

The modeling domain was selected to be 370×320 km (37×32 grid mesh), which coincides with the area of Atlanta's air quality model. To resolve individual fair weather cumuli the grid spacing should be about 1 km or even less. Thus, three nested grids were employed with decreasing grid spacing of 10 km, 3.3 km, and 1.1 km. The coarse grid is dimensioned 37×32 grid points, the second grid has 32×32 grid mesh. The finest grid, dimensioned 38×38 , encompasses almost all of downtown Atlanta. All three grids have 26 grid points in the vertical and 8 levels in the soil model. Vertical resolution increases with height from 25 m at the bottom to 2500 m at the top of the model domain at 10,500 m. The soil levels are: 25, 21, 17, 13, 9, 6, 3 cm and the surface ($z=0$). The model's top boundary condition was set as a rigid lid (or wall on top). The Klemp–Wilhelmson radiative condition (Klemp, Wilhelmson 1978a, b) was applied as the lateral boundary condition, in which the normal velocity components are advected from the inside of the domain. For the rest of variables the zero gradient condition was prescribed. The bottom boundary condition is supplied by the soil/vegetation model which prognoses the surface temperature and the surface moisture.

Land use/cover classification is based on BATS (Biosphere Atmosphere Transfer Scheme) (Dickinson et al., 1986), which recognizes 18 land use/cover classes. Since there is no urban class in the BATS scheme, a substitute had to be constructed. Desert and semidesert were selected as a base for the urban classification. However, some adjustments were necessary; the surface roughness was increased to 1.0 m, the albedo decreased to 0.15, and the emissivity changed to 0.9. USGS (US Geological Survey) land use/cover data set with horizontal resolution of 200 m was used to create an urban mask which would overwrite the default BATS land use/cover class. An example of “urban” and “nonurban” land use/cover parameters is in Figures 5a and 5b. Figures 5c and 5d show the land use categorization for urban simulation for grids 2 and 3, respectively.

The net effect of land use/cover is determined as a difference between two numerical simulations: urban and control (“nonurban”). The urban run includes the city in all relevant parameterizations: albedo, surface roughness, soil textural class, vegetation type and cover. The control simulation is achieved by replacing the city in the model by the natural land use/cover characteristics of the city's surroundings. In other words, the control run simulates an environment undisturbed by urbanization. In Figure 5 the urban areas marked by red are

replaced by natural land use/cover, which, in the case of Atlanta, happened to be crop/mixed farming.

The effect of clouds on surface variables is estimated as a difference between the urban run with explicit microphysics and the corresponding “dry” run without clouds at all (microphysics “turned off”). The difference would correspond to the net surface effect of clouds.

2.1.2.2 Results

Dates 21 and 23 August 1996 were selected for numerical simulations. The reason for this selection is the clear sky conditions in the morning on both days with small fair weather Cumulus development later in the day. In addition, 21 August exhibited relatively low concentrations of ozone whereas 23 August showed high values of ozone, which may be a good case for the air quality comparison. Soundings taken at Peachtree City at 1200 UTC (0700 LST) about 50 km southwest of Atlanta were used for model initialization.

2.1.2.2.1 The case of 21 August 1996

On 21 August 1996 the synoptic situation can be described as a high pressure area stretching over the whole Southeast, which is favorable setting for small clouds development. The clear-sky condition is an advantage for the RAMS’ initialization since the cloud field does not need to be initialized at the beginning of the model run. After initialization, the model was run for 8 hours beginning at 0700 LST (1200 UTC) for each three simulations: urban, nonurban, and dry “no clouds” case.

The difference between the urban and nonurban runs is taken as the net urban effect on various parameters. Our focus is on the finest grid covering downtown Atlanta since it can resolve small clouds. The urban effect on skin surface temperature is shown in Figure 6, which correspond to the time of the maximum urban heat island intensity at 1300 LST.

The urban heat island does not show uniform structure; there are warmer and cooler spots. The warmest point is about $+3.5^{\circ}\text{C}$ on the eastern side of the city. Some “cool” islands are in the middle of the city, exhibiting about -1.7°C perturbations. This inhomogeneity is largely the effect of clouds, as they would develop differently in an urban and corresponding natural environment. The temporal evolution of the urban heat island at the point of maximum magnitude (red cross in Figure 6) is shown in Figure 7. The oscillating nature of the urban heat island is due to clouds as they pass over this particular point. This shading effect is clearly demonstrated in Figure 8, which shows the surface energy components for the urban simulation. The incoming radiation (shortwave and longwave combined) shows oscillation through the day as the result of cloud shading.

The net effect of clouds on the skin surface temperature is depicted in Figure 9, which shows predominately negative values; however, there are some areas with positive magnitude. The negative skin surface temperature is the result of the cloud shading. The maximum cloud cooling effect is about -5.0°C located close to the eastern boundary. The areas with positive values are small and their magnitude is less than $+0.5^{\circ}\text{C}$ ($+0.44^{\circ}\text{C}$ max.). They probably occur in areas which are not cloud shaded and, thus, represent the urban heat island effect unmodified by clouds. The temporal evolution of the cooling effect on the skin surface temperature at the point of its maximum (red cross in Figure 9) is in Figure 10.

Unlike the urban effect the cloud effect does not oscillate, but it gradually drops down to about -5.0°C (1300 LST) and then it slowly increases.

However, due to the still unpredictable nature of convection and convective clouds, it is not possible to determine the exact location of warm or cool spots; rather, modeling results give overall information in a statistical sense. In other words, those are the maxima and minima that can be expected somewhere in the area. To estimate the overall effect of either urbanization or clouds, averages of the skin surface temperatures over the finest grid 3 were calculated, and the results are shown in Figure 11. The urban effect is positive, implying a heat island, then it slowly decreases its magnitude in time. The cloud effect starts at zero, and after the time of cloud onset it begins to drop gradually up to -2.5°C . From this follows that the urban warming effect takes place at any time, but it is in less magnitude than the cloud effect. The cloud effect gets stronger with time as more clouds develop, reaching a magnitude of -2.5°C later in the afternoon.

The effect of urbanization on clouds is presented in Figure 12, which is the comparison of fractional cloud cover for the urban and nonurban simulations. The threshold for “cloudiness” was set at a mixing ratio of 0.3 g/kg of total condensate. It is seen that the onset of convective clouds is at the same time for both urban and natural land types. In the morning more clouds tend to develop over the urban area as compare to natural land. In the afternoon it is the opposite; natural land use/cover type of environment would experience more clouds than corresponding urban landscape. Possible explanations will be discussed in the next section.

The GOES 8 visible data were utilized to compare and verify the modeled cloud fields. Since grid to grid comparison of individual clouds would not yield any significant correlation due to somewhat random nature of convective activity, the average fractional cloud coverage for the finest grid 3 was calculated. The comparison of modeled and observed cloud coverage is in Figure 13. RAMS tends to start convective clouds earlier by about 20–30 minutes than the observed onset of convective Cu. In the morning hours, the difference between modeled and observed cloud coverage is within 10% and both patterns are very similar. However, in the afternoon RAMS continues to produce clouds as opposed to GOES 8-observed clouds, which decrease in time. The possible reasons for the overestimation of clouds in RAMS model will be discussed in the next section.

2.1.2.2.2 The case of 23 August 1996

The synoptic situation for 23 August was similar to that two days prior (21. August). The high pressure system that developed over Southeast was slowly weakening.

The urban effect on the skin surface temperature at the time of the maximum intensity (1300 LST) is in Figure 14. As in the previous case there are warmer and cool spots within the smallest grid 3. The coolest areas show the “cool” island of about -1.5°C or less; the maximum of the heat island in the city is about 3.0°C (denoted by the red cross in Figure 14). There is another maximum at the northeast city’s boundary exhibiting $+3.5^{\circ}\text{C}$ heat island (the maximum value underlined in Figure 14). The temporal evolution of the urban heat island at the point of its maximum is given in Figure 15. The magnitude of the urban heat island shows oscillations as in the first case, which is the effect of cloud shading. The amplitude of these oscillations is smaller compared to the first case, which may be due to fewer clouds in

this case. The time when the first convective clouds appeared is about 1015 LST in this case, which is about the same time as in the first case. However, the overall cloud cover is less through the day on 23 August than that on 21 August (c.f. Figures 13 and 21). Figure 16 shows the surface energy components in time at the point of the maximum urban heat island. It shows much less fluctuation of all components, including the incoming radiation, than in the first case (c.f. Figure 8).

The cloud effect on the skin surface temperature is given in Figure 17, corresponding to the time of the maximum intensity (1300 LST). The majority of the urban area exhibits negative values, which indicates the cooling effect of clouds. There are a few small spots with positive magnitudes. The maximum is about $+0.77^{\circ}\text{C}$ on the west side of the city (maximum value underlined in Figure 17). The minimum, or the largest cooling, occurred on the east side of the city (denoted by the red cross in Figure 17) with a magnitude of -3.8°C . The temporal evolution of the cloud cooling effect at the point of its maximum (grid 33,21) is presented in Figure 18. During the first two hours, there are no clouds; thus, no effect can take place. Later on as more clouds developed the cooling effect became stronger. The maximum cloud cooling peaked at 1300 LST and weakened afterwards. The averaged urban and cloud effects over the smallest grid 3 are given in Figure 19. As on 21 August, the urban effect shows positive values, implying a heat island. The effect of clouds is cooling. The magnitude of the urban effect shows little oscillation through the day. The cooling cloud effect increases with time as a response to more cloud shading.

The effect of urbanization on clouds is presented in Figure 20 which shows the comparison of urban and corresponding nonurban modeled clouds. The basic difference between this case and the first one is that fewer clouds developed over the urban area than over the corresponding natural land use/cover. In the first case the urban area tended to increase cloudiness in the morning and decrease it in the afternoon. In this case there is a constant increase of cloudiness over the natural environment.

The comparison of observed and modeled clouds in terms of fractional cloud coverage is given in Figure 21. As in the first case, RAMS overestimated the cloud coverage, especially early in the day and later in the afternoon. In the morning RAMS biased cloud cover by 25%. The closest match of RAMS and observed clouds is around noon when the difference is about 10% or less. The possible reasons for RAMS overestimation of clouds are discussed in the next section.

2.1.2.3 Discussion and Conclusions

Mesoscale models, and RAMS in particular, can provide information on the effects of urbanization and clouds on various surface variables. The major benefit of modeling is that it provides more information than in situ or remote sensing observations and, in addition, the physics is resolved at each grid point. RAMS can simulate small convective clouds in promising agreement with GOES 8 observations.

The results show the effect of land use on surface temperature and cloud fields. Urbanization increases the skin surface temperature by about $1.0\text{--}1.5^{\circ}\text{C}$ on average under cloudy conditions. The extreme values of the urban heat island can be up to $+3.5^{\circ}\text{C}$. Clouds cool the surface due to their shading effect. The average cooling is about $1.5\text{--}2.0^{\circ}\text{C}$ and increases with time as more clouds develop. The extreme value can be up to -5.0°C . Though

larger in magnitude than the urban heat island effect, the cloud cooling effect that takes place only when there are clouds. In this case the time of the maximum intensity of the cloud effect corresponds to the peak of convective activity, which is usually in the early afternoon.

The effect of Atlanta on small Cu clouds is a slight increase (~10%) in the morning hours and a reduction in the afternoon (<10%) in the case of 21 August. The possible reasons for the morning increase of cloudiness over the urban area may be the urban heat island itself. A warmer surface will enhance vertical upward motion resulting in more clouds. The afternoon reduction may be the blocking effect of a rough city that would reduce the advection of already developed small Cu clouds into the city from the outside (Bornstein and LeRoy, 1990). However, RAMS does not model this blocking effect well. Thus, the afternoon reduction is more likely the result of decreased moisture in the city as compared to natural surroundings. The moister natural land would slow convection in the morning due to lower skin surface temperature, but it would provide more moisture for the afternoon clouds. In the second case (23 August) there is a significant reduction of cloudiness by the urban type of land use/cover (Figure 20). This enhancement by the natural cover can be over 10% (see Figure 20 at 1100 LST). The slight reduction of natural land type cloud cover in the afternoon does not seem to be significant. The vertical profiles of relative humidity, which are given in Figure 22, may help to explain less “urban” clouds in the second case. The sounding for 21 August is relatively more humid than that for the second case up to about 3500 m. The only exception is a layer between 900 and 1100 m. At present it is uncertain whether the initial profile of relative humidity is the main cause of the different behavior of the modeled clouds over urban and natural land cover as seen in Figures 12 and 20. It seems that if the initial moisture is sufficient, natural land cover would enhance cloudiness as opposed to the less moist initial vertical profile (the case 21 August).

The comparison of modeled and observed cloud cover reveals that RAMS tends to overestimate the cloud especially in the afternoons, which makes the afternoon results somewhat uncertain. The possible reasons for RAMS’s cloud overestimation could be the numerically overpredicted advection of clouds from the coarser grid 2 into the grid 3. Since the coarser grid 2 has grid spacing of 3.3 km, it cannot effectively resolve small cumuli and tends to overestimate the cloud amount and water content (M. E. Nicholls 1997, personal comm.).

The other reason could be the surface parameterization. The RAMS is rather sensitive to the surface parameters especially vegetation and the leaf area index (LAI) (P. L. Vidale, 1997, personal comm.). The values of albedo, soil textural class parameters, soil moisture, vegetation fractional coverage and LAI as prescribed in the model may not be representative for a given grid point. Larger values of LAI increase the transpiration of water from the vegetation, which means more moisture is available to form more clouds than in a dry air. The same applies in the case of larger vegetation fractional coverage.

2.2 Year 2 Accomplishments and Results

In Year 2 of the project, we again divided the work into observational and modeling components.

2.2.1 GOES observations

2.2.1.1 *Cloud climatology*

To study the role of small convective clouds in the environment of the city of Atlanta, GOES visible images were chosen. Data gathered during the period 5 July – 5 September 1996 were used. The following threshold technique was used to discriminate cloudy from clear pixels. First the visible reflectance data were converted to albedo by dividing the reflectance at each pixel by the cosine of the solar zenith angle. Then a minimum albedo image was constructed for each time of observation (i.e., each half hour). The threshold between clear and cloudy pixels was derived as the minimum albedo digital count + 30 digital counts (30 digital counts correspond to an increase of 7.5% in albedo). Finally, each pixel in each image was classified as either clear or cloudy.

Fractional cloud cover images for five times of the day are shown in Fig. 23. Some features in cloud coverage field are clearly visible, such as the mountainous region north of Atlanta and also some lakes.

As seen on Fig. 23, it is quite difficult to distinguish Atlanta's urban area in the cloud cover field since there is a considerable degree of variability across the region. A slight increase of cloudiness over Atlanta can be detected in Figs. 23b and 23c, which are enlarged in Figs. 24a and 24b.

To examine the effect of the urban area on cloudiness under calm, fair-weather conditions, a 10-day period (15–24 August 1996) was selected. Year 1 research showed that these days were clear in the morning and dominated by small cumulus clouds in the afternoon. They also had higher than normal ozone concentrations in the afternoon. Figure 25a (and 25b) shows cloud cover for that 10-day period at 1245 UTC. Fog in the valleys north of Atlanta is quite obvious as is the dark, clear conditions in and around Atlanta. There is a localized maximum of cloudiness just in the center of Atlanta. Since 1245 UTC is 0745 local standard time (LST) and calm, high-pressure weather conditions existed, it is most likely fog or haze rather than convective clouds. Later in the day, the situation changes. Figures 26a and 26b show cloud cover at 1745 UTC (1245 LST). Cloudiness is now much more widespread and spatially variable. The effect of the city on cloud cover is difficult to distinguish. There is a region of slightly enhanced cloudiness in the center of Atlanta, but there are also such areas elsewhere. Still later in the day (Figs. 27a and 27b) at 2015 UTC (1515 LST) there is a definite maximum of cloudiness across the center of Atlanta.

The cloud calculations for each image as well as the cloud frequency for the entire 63-day period and for the 10-day, clear-in-the-morning days are available for comparison with model results and with other data.

2.2.1.2 *Relationship between land use/cover and cloudiness*

One of the goals of this study is to begin to understand the connection between land use/cover and cloudiness. As a start in this quest using the cloud data determined from GOES visible data (see above), we attempted to correlate cloud frequency with the degree of

urbanization. From C. P. Lo of the University of Georgia, we obtained land use/cover maps generated from 1997–98 Landsat Thematic Mapper (TM) data. The original maps have very high resolution (25 m) compared to the 1 km resolution GOES data. Therefore, we averaged the TM data to a 1 km \times 1 km grid by calculating the fraction of the 1 km \times 1 km grid area that is “urban,” i.e., a value of zero means no urban class within a given grid square; a value of one corresponds to completely urban land use. The map is shown in Fig. 28. This map of “degree” of urbanization was correlated to the cloud climatology maps described above, and the results are shown in Fig. 29. Fig. 29a shows the correlation coefficients for all 63 days; Fig. 29b shows the correlation coefficients for only calm, fair-weather conditions (15–24 August 1996). Results for all 63 days show higher correlation between urban land use/cover and fractional cloud cover in the morning than in the afternoon. Correlation coefficients for calm fair weather conditions are weak.

2.2.1.3 Cloud data for air quality modeling

We collected GOES data for the period 27 July–3 August 1997, converted them to cloud cover information, and sent them to Haider Taha for use in the air quality model he is using in another part of the larger ATLANTA project. Air quality models typically assume no clouds. We hope that the running the air quality model with and without clouds will determine what effect the clouds have on ozone concentration.

2.2.2 RAMS modeling

2.2.2.1 Cloud modeling

To understand the effects of changes in land use/cover on clouds, numerical models must be employed. The CSU–RAMS numerical model has been chosen to carry out these simulations. The effect of Atlanta on small cloud development was simulated as a difference between two model runs: the first with the city included in all relevant model parameterizations and the second with the city replaced by natural land use/cover characteristics. Numerical simulations were completed for 4 consecutive days: 21, 22, 23 and 24 August 1996. A triple-nested grid was adopted with grid spacings of 10 km, 3.3 km and 1.1 km. The area covered by the largest grid is shown in Fig. 30

After completion of urban and non-urban simulations, the difference is attributed to the effect of the city. First the effect on cloud cover was examined. Results for all four days are shown in Fig. 31, which is the fractional cloud cover over the finest grid 3 for urban and non-urban simulations. The threshold to determine cloudy and clear grids was set to 0.3 g/kg of cloud condensate (i.e., cloud water plus ice). As seen in Fig. 31 there is no systematic trend in the effect of the city on cloudiness. On 21 August there is an increase of urban clouds in the morning and then in the afternoon a decrease. The case of 22 August shows increased nonurban cloudiness almost all day. On 23 August nonurban cloudiness is greater than urban clouds in the morning; in the afternoon the situation reverses. The last day, 24 August, shows almost no difference between urban and corresponding nonurban clouds. Thus, any conclusion based on model simulation is not quite possible yet.

The second cloud characteristic parameter studied was the height of cloud base. The results are given in Fig. 32, which shows the cloud base height averaged over the finest grid 3 for both urban and nonurban simulations. The urban clouds exhibit slightly higher heights than corresponding nonurban clouds, which is especially noted on 21 and 24 August in late morning hours.

2.2.2.2 *Verification of modeled clouds*

GOES visible observations were compared to the RAMS modeled cloud amounts over the finest grid 3 for four days (21–24 August), which is shown in Fig. 33. Based on GOES-observed and RAMS-modeled cloudiness it is seen that the model tends to overestimate clouds in terms of the cloud amounts and in terms of the time of small Cumulus initiation. Small cumuli start to develop at about 1545 UTC on 21 August and at 1645 UTC on 22, 23 and 24 August. However, RAMS starts to produce clouds at about 1400 – 1500 UTC, which is almost 2 hours earlier. Also the RAMS-simulated cloud cover is much higher than corresponding GOES observations. This may be due to improper values of soil and surface moisture parameters (Louie Grasso, 1998, personal comm.). The values of soil moisture content and leaf area index (LAI) determine the upward moisture flux, which can increase humidity at upper levels. Unrealistically high moisture content in the higher levels can result in the RAMS model producing more clouds and at earlier times. The leaf area index and especially soil moisture content are variables which are difficult to obtain and usually have to be estimated based partially on RAMS numerical tests.

2.3 Year 3 Accomplishments and Results

During the final period of the grant (“Year 3”) we concentrated on trying to fill in gaps in our knowledge.

2.3.1 Observed urban-rural cloud variations

Previously we had modeled urban-rural cloud differences, and we had correlated GOES-observed clouds with Landsat-derived urbanization. Now we wanted to get a more direct comparison of cloudiness in the urban and surrounding rural area. Figure 34 shows “urbanization” (red) with mean cloud cover (green) at 1915 UTC on “clear” morning cases. Yellow areas are those which are both urban and cloud covered. The inner circle encloses the “urban” area for the next figure. The area between the two circles represents the surrounding “rural” area. It also represents the rural area which could be affected by urban-induced circulation.

Figure 35 shows the fractional cloud cover in the urban and surrounding rural area for all 63 days and for the 10 clear-in-the-morning days. In both cases, the urban area tends to have more cloudiness, which is consistent with a warmer urban area inducing a circulation which is upward (and enhances clouds) over the urban area and is downward (and suppresses clouds) over the rural area which immediately surrounds the urban area.

2.3.2 Observed cloud-ozone relationship

Figure 36 shows the location of the Atlanta-area air quality monitoring stations in 1996.

Figure 37 shows the correlation between ozone concentration and fractional cloud cover at each of the air quality stations. In general (all cases), there is an inverse relationship between ozone and cloudiness. For clear-in-the-morning cases, which are dominated by high pressure, low wind situations and which tend to have more ozone, there is a positive correlation between ozone and cloudiness except at rural Yorkville.

2.3.3 Mapping

The RAMS model runs on a Universal Transverse Mercator (UTM) grid. It is clear that the satellite and other data would be more useful if they were placed on a common map grid. Figure 38 shows a GOES image mapped onto a UTM grid with the three nested RAMS modeling grids overlaid. We believe that in the future all data should be mapped to a common map projection for ease of comparison.

2.4 References

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Weinreb, M., M. Jamieson, N. Fulton, Y. Chen, J. X. Johnson, Smith, J. Bremer, and J. Baucom, 1997: *Operational Calibration of the Imagers and Sounders on the GOES-8 and -9 Satellites*. NOAA Tech. Memo. NESDIS 44, Washington, DC, 32 pp.

3 Conclusions

Our cloud research can be broken into two questions: (1) what is the effect of land use/cover on clouds, and (2) what is the effect of clouds on climate and air quality? Answering these two questions will, we hope, answer the question of what role clouds play in the land use/cover—climate/air quality connection, which is the overall goal of Project ATLANTA. Symbolically, one can represent this work as

$$\frac{\partial Q}{\partial L} = \frac{\partial C}{\partial L} \frac{\partial Q}{\partial C} + other_factors$$

where Q represents climate and air quality, L represents land use/cover, and C represents clouds. Each term has an observational component and a modeling component. We present the conclusions of our research organized into four themes: (1) observing the $\partial C/\partial L$ term, (2) modeling the $\partial C/\partial L$ term, (3) observing the $\partial Q/\partial C$ term, and (4) modeling the $\partial Q/\partial C$ term.

3.1 Observing the $\partial C/\partial L$ term

In the observational component, we use GOES images to determine cloudiness. In Year 1 we learned that there are essentially two types of days in Atlanta in the summer: those that are clear in the morning and those that cloudy in the morning. Clear-in-the-morning days are dominated by small cumulus clouds in the afternoon and tend to have higher ozone concentrations. Cloudy-in-the-morning days represent “disturbed” weather, and are less important from an air-quality point of view (Section 3.3).

In Year 2 we formulated a technique to classify each pixel in the visible GOES imagery as either clear or cloudy and we obtained from C. P. Lo an “urbanization” map based on Landsat data. Correlations between urbanization and cloud cover are shown in Fig. 29. When all 63 days are considered, there tends to be a positive correlation between cloud cover and urbanization in the morning and a slight negative correlation in the afternoon. When only clear-in-the-morning days are considered, this relationship tends to reverse; the correlation is negative in the morning and positive in the afternoon. We aren’t sure exactly what this means, but it could be important for air quality because the clear-in-the-morning days tend to be high ozone days.

In Year 3 we learned that there always tend to be more clouds over the urban area than over a ring of surrounding rural area (Figs. 34 and 35). This is consistent with the urban warming effect, which would produce rising air and more clouds over the city and subsidence and fewer clouds over the surrounding area.

3.2 Modeling the $\partial C/\partial L$ term

Using the RAMS model, we have found that

- urbanization increases the skin surface temperature by about 1.0–1.5°C on average under cloudy conditions, with an extreme of +3.5°C (Figs. 11 and 19).
- clouds cool the surface due to their shading effect by 1.5–2.0°C on average, with an extreme of 5.0°C (Figs. 11 and 19).
- RAMS simulates well the building stage of the cumulus cloud field, but does poorly in the decaying phase (Figs. 13 and 21).
- An improved version of RAMS does better with decaying clouds, but produces consistently more clouds than observed (Fig. 33).
- RAMS simulations over grid 3 give inconsistent results as to the difference between urban and rural cloudiness (Figs 12, 20, and 31). In part, this is because grid 3 is almost all urban. What we really need to do is compare grid 3 cloudiness with grid 2 cloudiness, essentially as we did with GOES-observed cloudiness. However, because grid 2 has coarser resolution than grid 3, it cannot resolve the clouds, so comparison between grids is meaningless.

3.3 Observing the $\partial Q/\partial C$ term

Using maximum ozone concentration as an index of air quality, clear-in-the-morning days tend to have worse air quality than cloudy-in-the-morning days (Fig. 3). This makes sense because cloudy-in-the-morning days represent “disturbed” weather conditions in which winds from synoptic-scale systems will mix the air and prevent the buildup of pollutants.

For non-disturbed days, clouds follow the solar insolation. During the building phase, ozone concentration also follows solar insolation, but during the decaying phase, it does not because the destruction of ozone is unrelated to radiant flux. (Fig. 4).

For urban stations, the correlation between peak ozone concentration and cloudiness is positive for non-disturbed (clear-in-the-morning) days (Fig. 37). We believe that the explanation for this is that for urban stations, hotter days have both more clouds and more ozone.

3.4 Modeling the $\partial Q/\partial C$ term

RAMS modeling shows that clouds significantly cool the surface by shading. Because clouds reflect ultraviolet light back to space, they probably also reduce the production of ozone, but we cannot model that with RAMS because it doesn’t include air chemistry. However, air chemistry modeling by Haider Taha shows that clouds dramatically decrease the production of isoprenes, which are ozone precursors. It is likely, therefore, that clouds significantly reduce ozone production. This point deserves much further study.

3.5 Summary

- Atlanta is a quite cloud place, and clouds definitely mediate the land use/cover–climate/air quality connection
- Clouds tend to counteract the warming effect of urbanization
- Mesoscale models are essential in understanding the role of clouds in the connection between land use and climate/air quality, but more work on the models needs to be done, especially in
 - Modeling of small clouds
 - Air chemistry modeling
- If you live in Atlanta, “Clouds are your friends”
 - They cool the surface
 - They reflect sunlight which might otherwise be used to produce ozone
 - The decrease biogenic emission of ozone precursors
 - They probably decrease ozone concentration, but our results are not yet definite.

3.6 Future work

This work brings up several new questions. Atlanta in the summer is hot, humid, and dominated by small cumulus clouds. It is also heavily forested. What would our results be if we chose a different city? Denver, for example, is much drier; yet it too has an ozone problem, particularly with the proposed 0.080 ppm federal ozone standard. What about a moist but less forested city? Trees act somewhat like wicks, transporting subsurface moisture into the atmosphere. A humid but less forested city—Houston, for example—would be another interesting case. Finally, a compact, heavily urban city typical of Europe could yield interesting insights in the relationship between land use/cover and climate and air quality.

Also, to completely understand the land use/air quality question, coupled mesoscale and air chemistry models need to be used.

4 Publications

4.1 Refereed Journal Publications

Hafner, J., and S. Q. Kidder, 1999: Urban heat island modeling in conjunction with satellite derived surface/soil parameters. *Journal of Applied Meteorology*, **38**, 448–465.

4.2 Conference Papers

Kidder, S. Q., and J. Hafner, 1999: Relationship between land use/cover and cloudiness over an urban area. Association of American Geographers Annual Meeting, 23–27 March, Honolulu.

Quattrochi, D. A., J. C. Luvall, M. G. Estes, C. P. Lo, S. Q. Kidder, J. Hafner, H. Taha, R. D. Bornstein, R. R. Gillies, and K. P. Gallo, 1998: Project ATLANTA (ATlanta Land use ANalysis: Temperature and Air quality) — A study of how the urban landscape affects meteorology and air quality through time. *Second Urban Environment Symposium*, 2–6 November, Albuquerque, NM. Boston: American Meteorological Society, 104–107.

4.3 Popular Press Publications

“Scalping of the Land Makes Atlantans Hot,” *The Atlanta Constitution*, 19 February 1999, p. A1.

“Rainy Night in Georgia, at Least in Atlanta.” *Science News*, Vol. 155, 27 March 1999, p. 198.

“Researchers Study Effects of Urban ‘Heat Island’,” *Space News*, 31 May 1999, p. 16.

“Hot Time in the City,” *Compressed Air*, September 1999, pp. 16–23.

“Hot Town: Heat Rising from Cities Appears to Be Changing Regional Weather Patterns,” *San Francisco Chronicle*, 6 March 2000.

“Scientists Watch Cities Make Their Own Weather,” *The New York Times*, 15 August 2000.

5 Figures

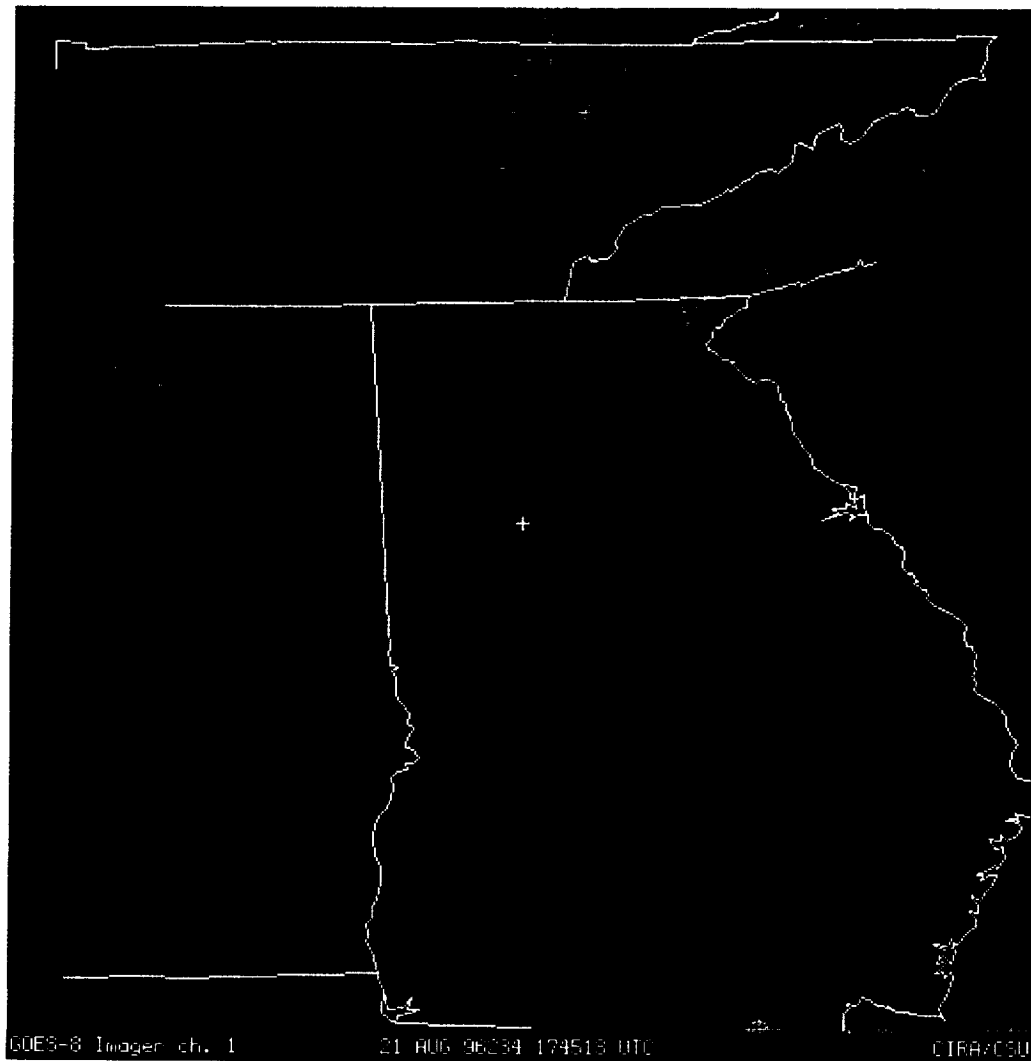


Figure 1. GOES 8 visible image of the Atlanta area. This is typical of otherwise clear days in the Southeast in the summer. Small clouds always break out in response to solar heating of a humid environment.

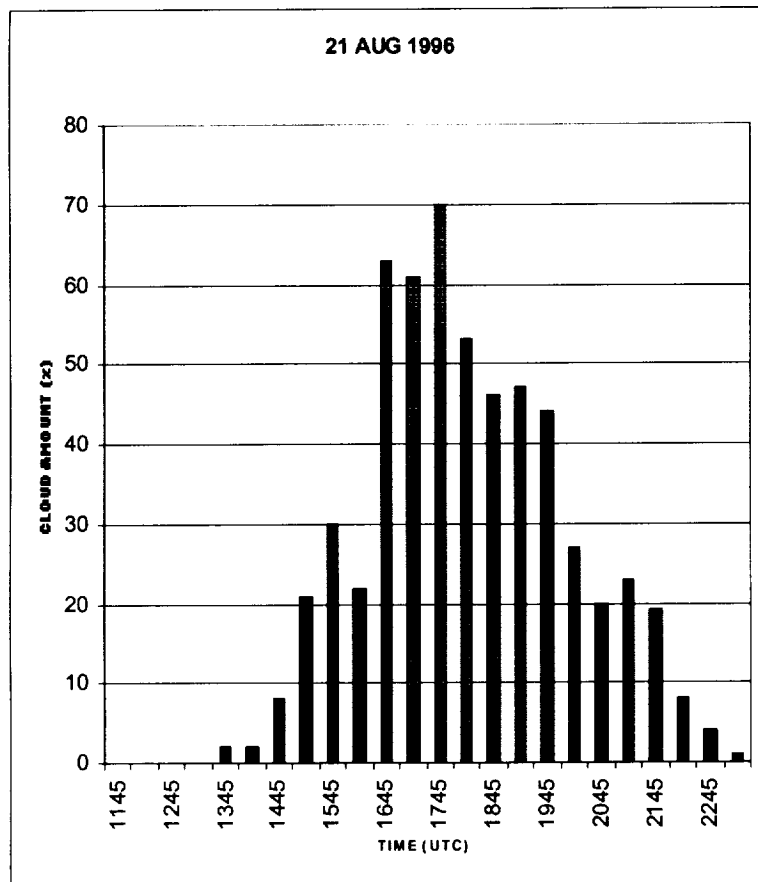


Figure 2. After correcting the GOES-measured radiance for the solar zenith angle, a histogram technique can be applied to determine the fraction of the area around Atlanta which are covered with clouds. The cloud cover rises and falls with solar insolation. This technique is preliminary, so that the calculated cloud amount cannot be considered final or exact, but at the peak of the afternoon cloudiness, over 50% of the area is cloud covered, which reflects sunlight back to space, cools the area, and possibly decreases the production of ozone and other photochemical species.

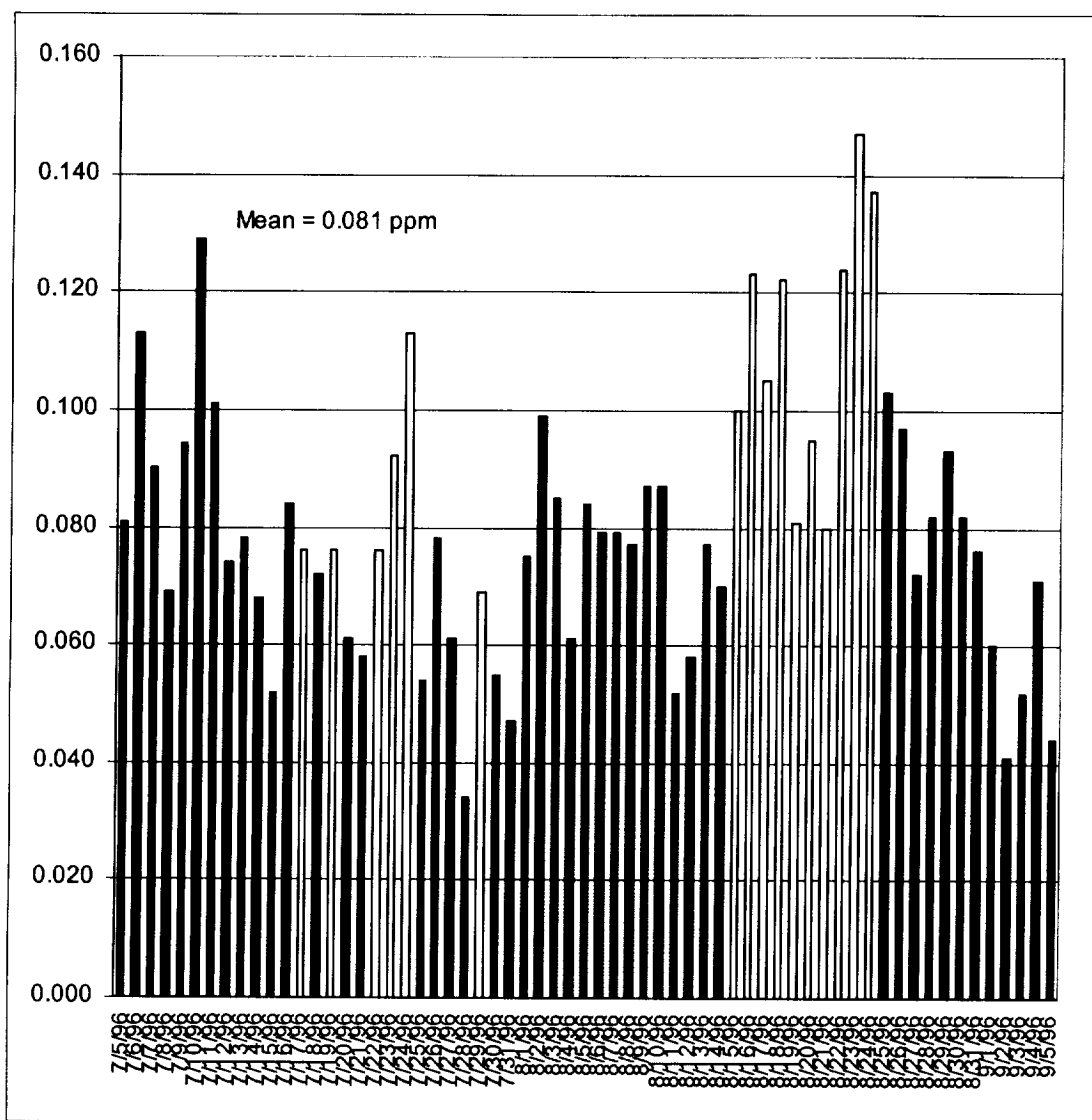


Figure 3. Days which are clear in the morning (white bars) tend to have higher ozone concentrations than days which are cloudy in the morning (shaded bars). Figure 1 is typical of the afternoon satellite images for these days. [Ozone data supplied by the Georgia Department of Natural Resources: <http://uam.air.dnr.state.ga.us/amp/index.html>.]

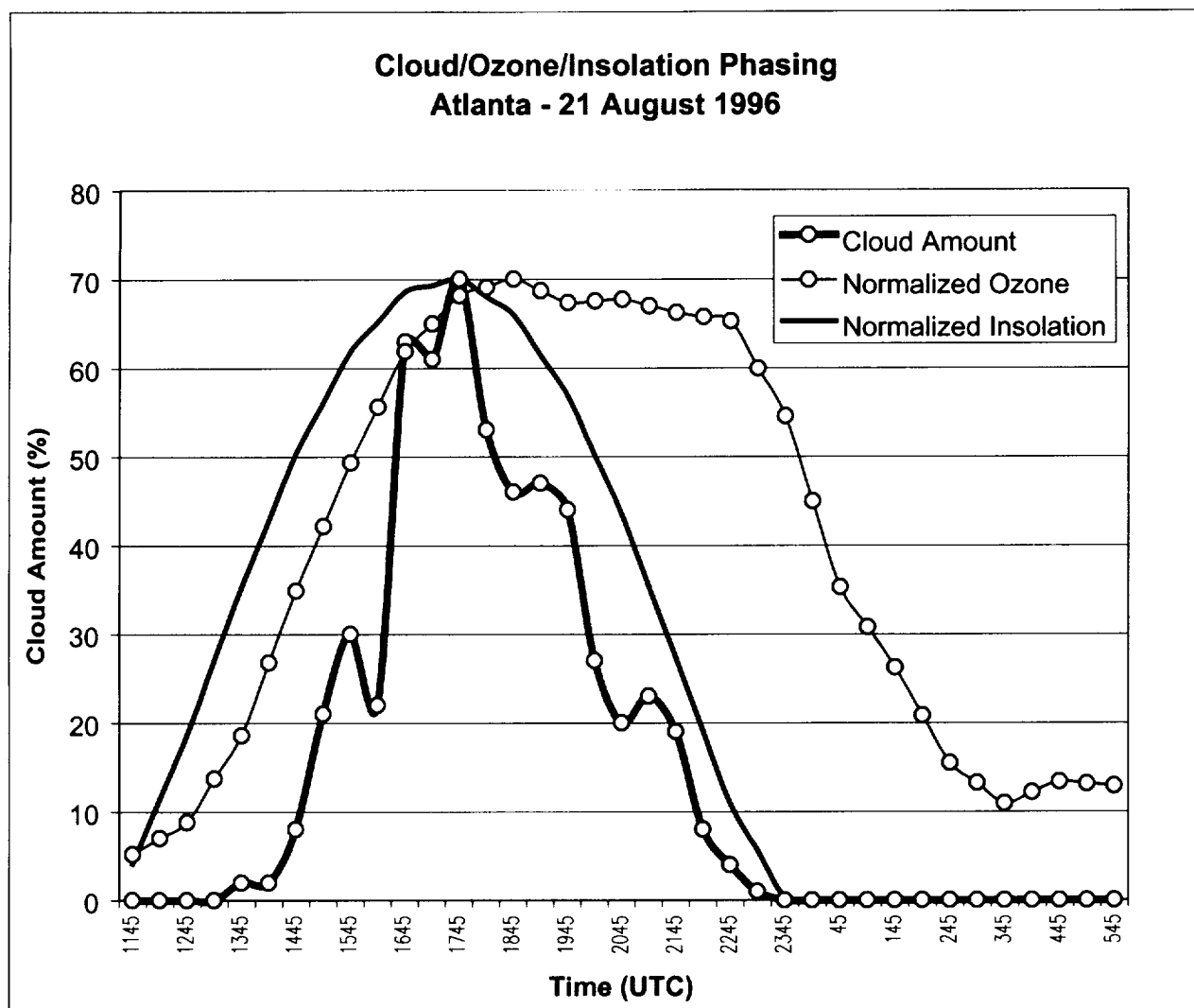


Figure 4. The relative phasing of clouds, ozone, and solar insolation for one day in Atlanta. Clouds and solar insolation are nearly in phase. The rise of ozone is in phase with solar insolation, but its destruction is not.

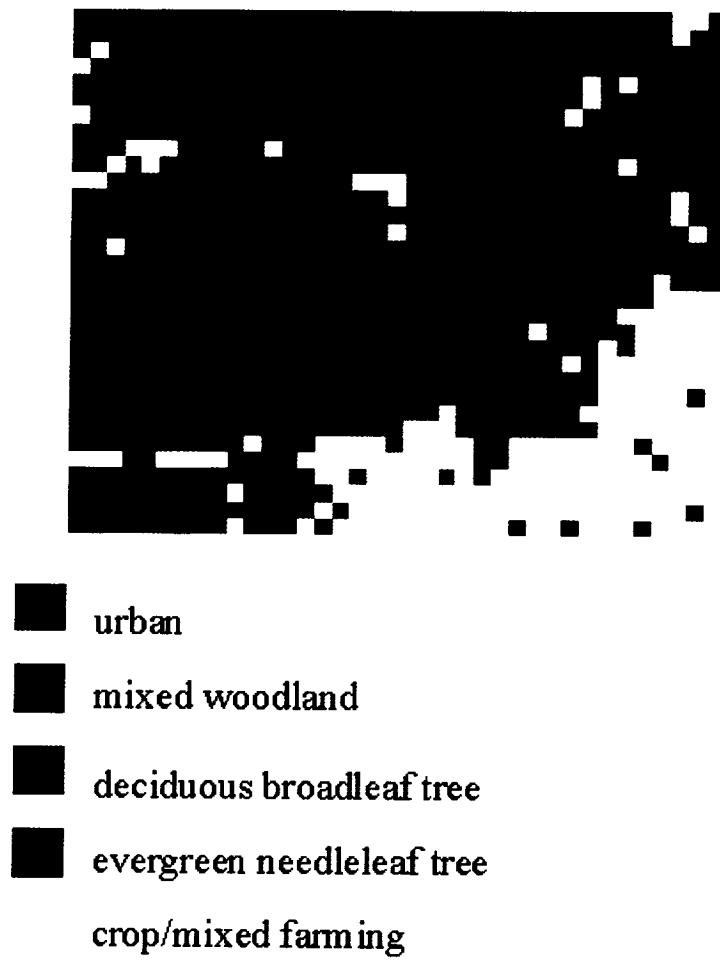


Figure 5a. Land use cover categorization for the grid 1 – urban simulation , 37 x 32 grids (370 x 320 km) with 10 km grid spacing.

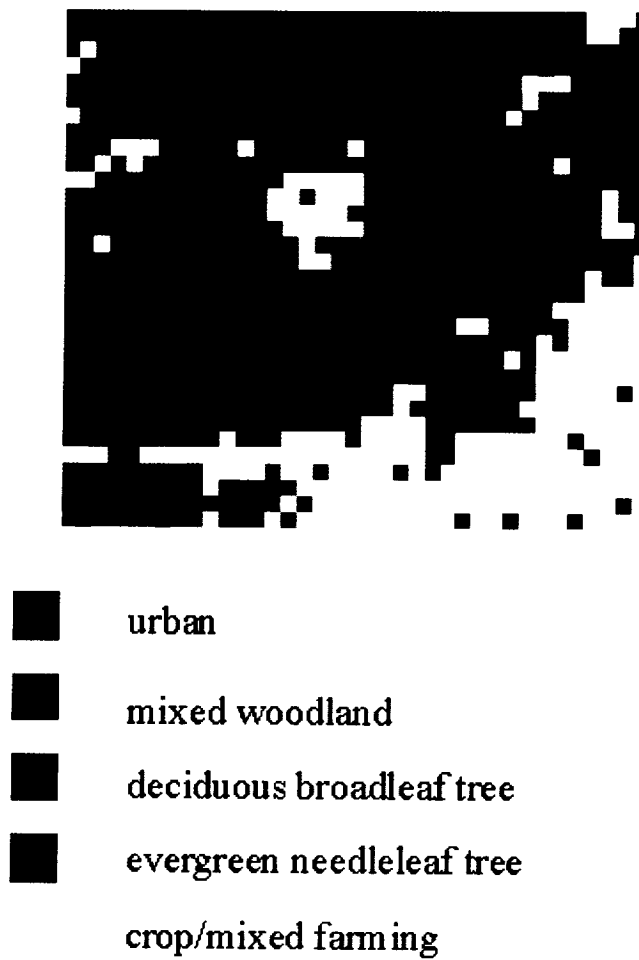


Figure 5b. Land use/cover categorization for nonurban simulation grid 1. The urban land type is being replaced by natural land cover.

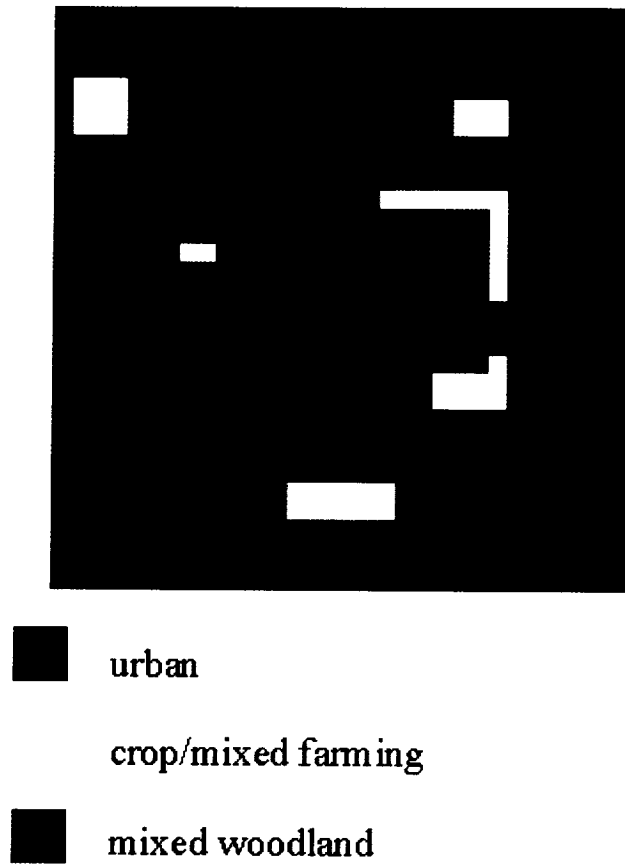


Figure 5c. Land use cover categorization for the grid 2. 32 x 32 grids (105 x 105 km) grid spacing 3.3 km (urban simulation).

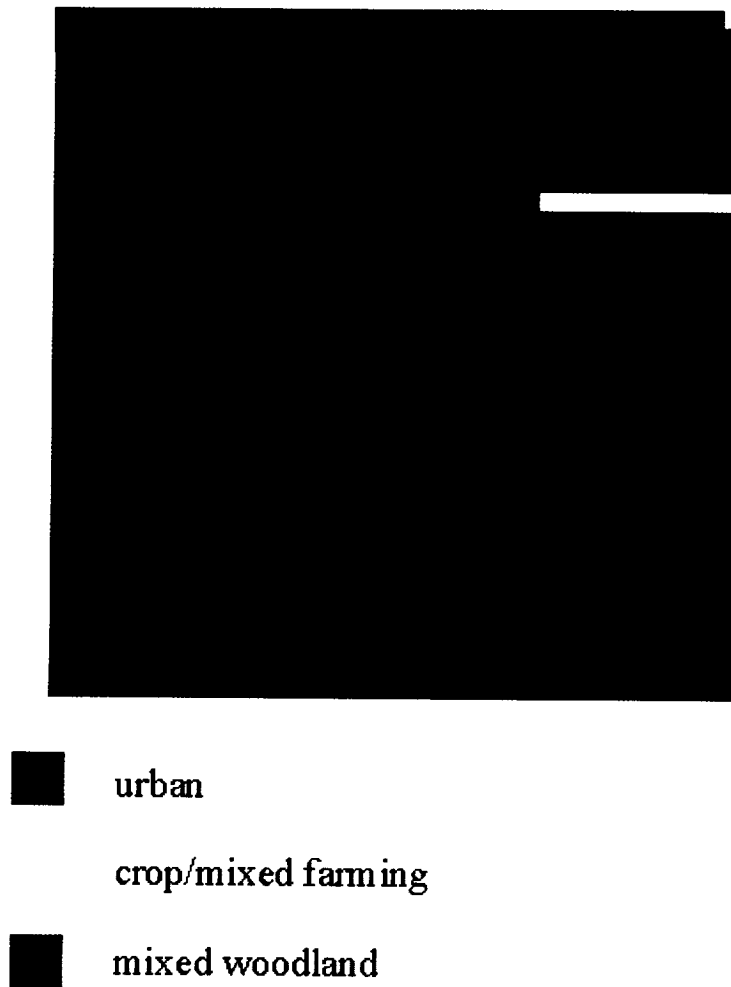


Figure 5d. Land use cover for the grid 3, 38 x 38 grids (42 x 42 km), grid spacing 1.1 km (urban simulation).

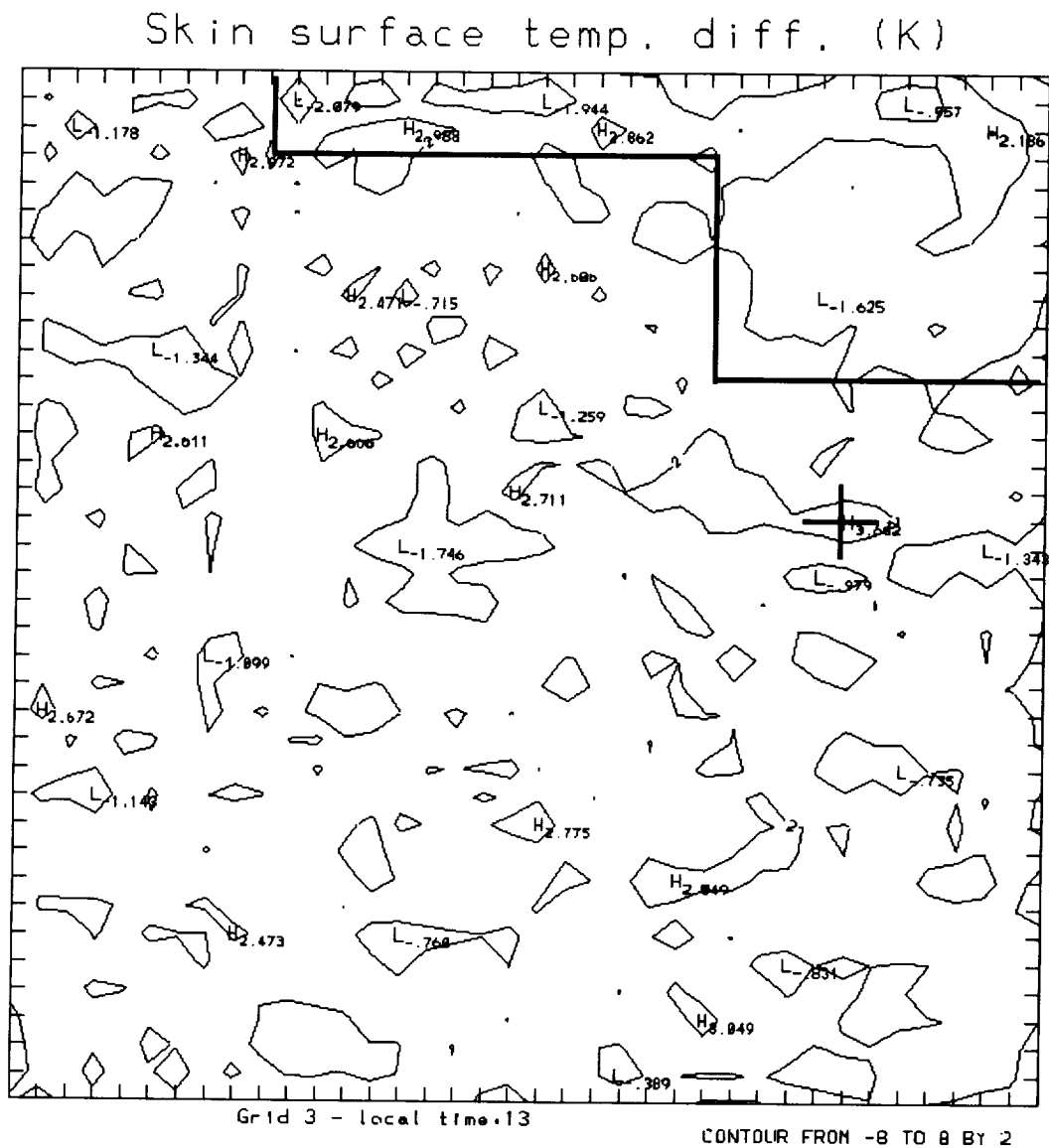


Figure 6. Urban heat island (K) in terms of skin surface temperature at the finest grid 3 at 1300 LST. The thick line marks Atlanta's boundary.

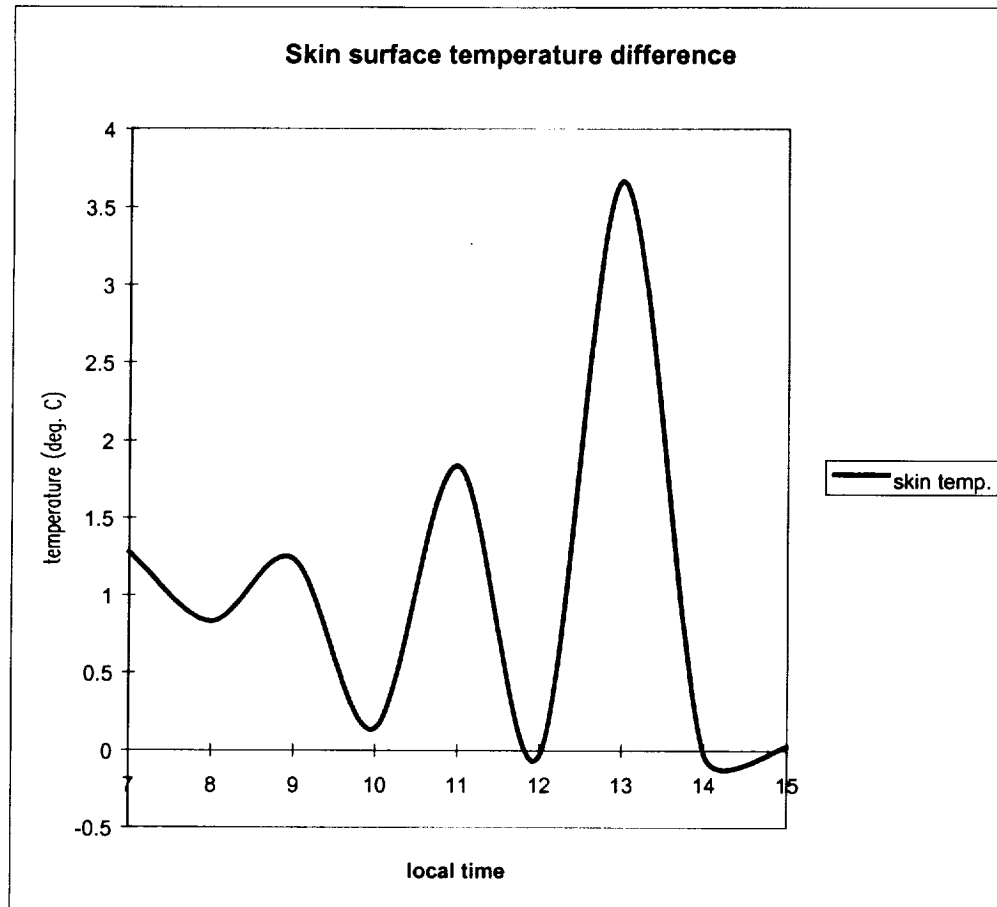


Figure 7. Temporal evolution of the urban heat island ($^{\circ}\text{C}$ skin surface temperature) at the point of its maximum (red cross in Figure 2).

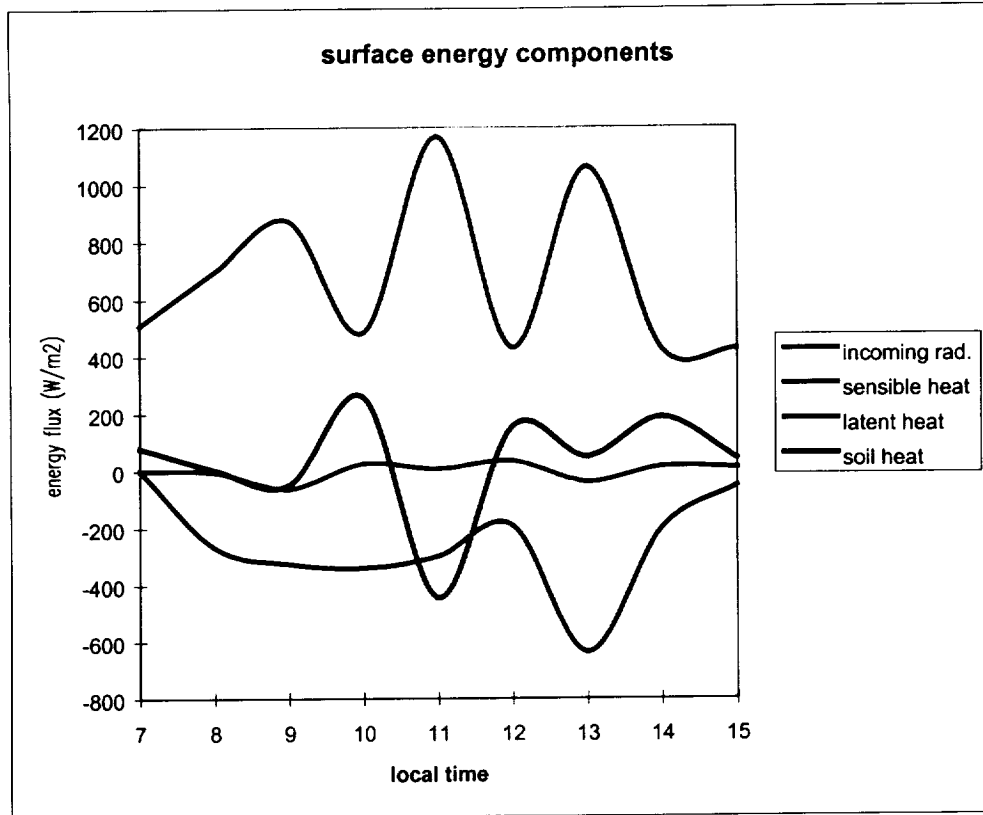


Figure 8. The surface energy components at the point of the maximum magnitude of the urban heat island (red cross in Figure 2).

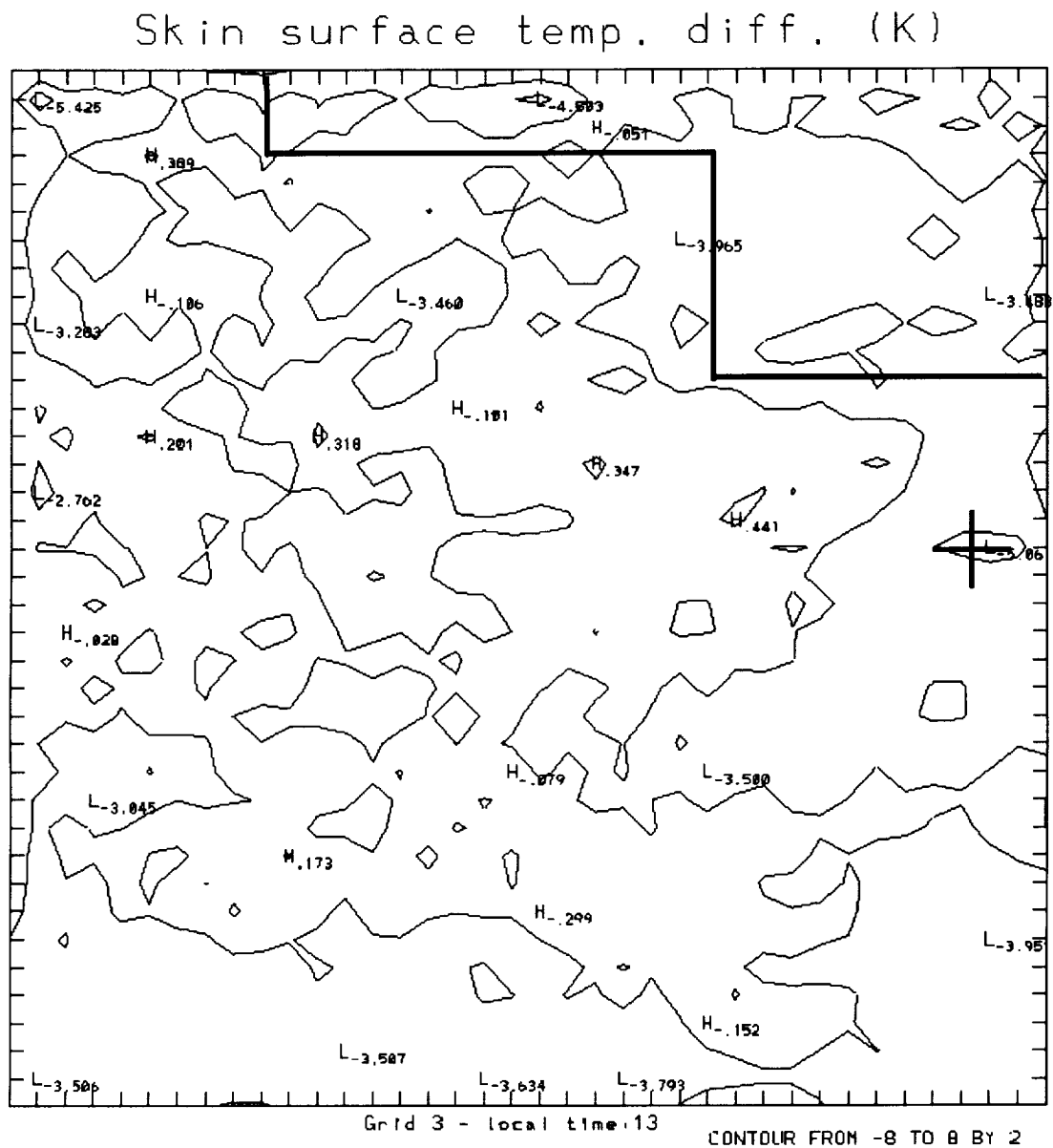


Figure 9. The cloud effect (K) on the skin surface temperature (grid 3). The thick line marks Atlanta's boundary.

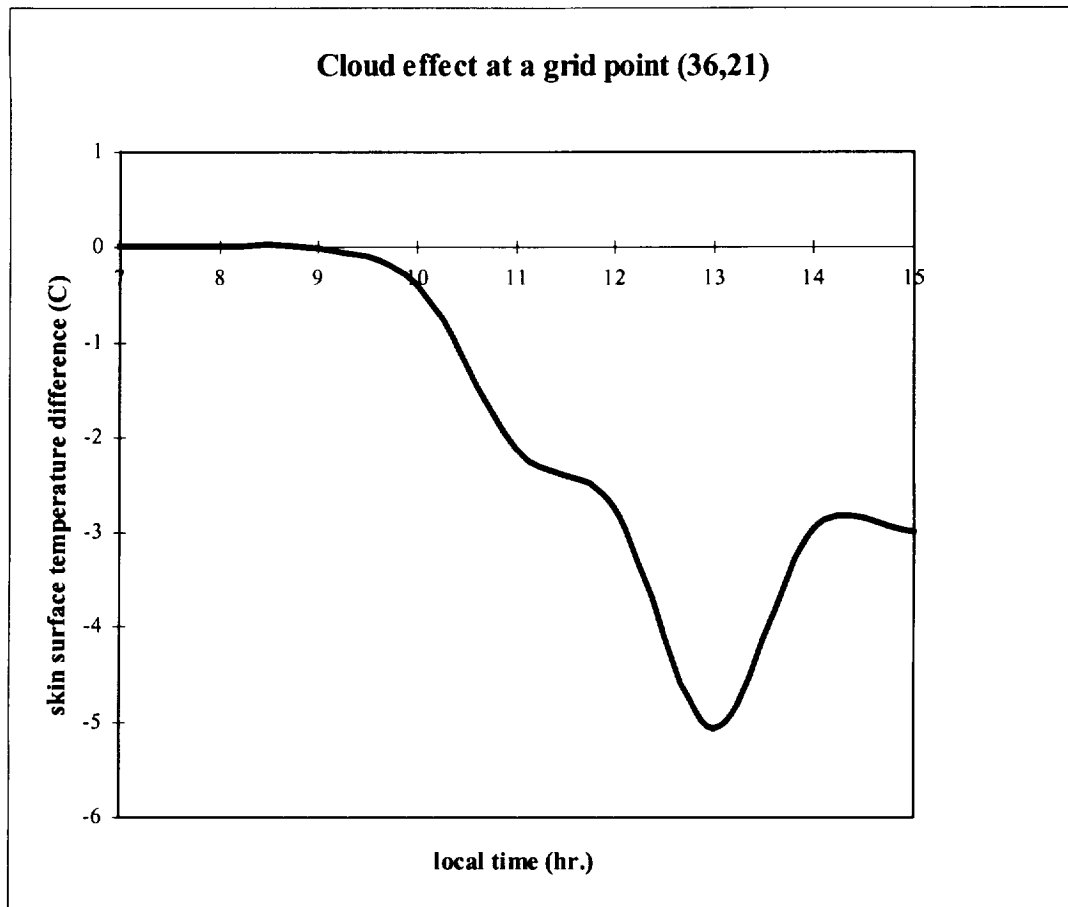


Figure 10. The cloud effect (°C) on the skin surface temperature at the point of its largest magnitude (denoted by the red cross in Figure 5), grid 3.

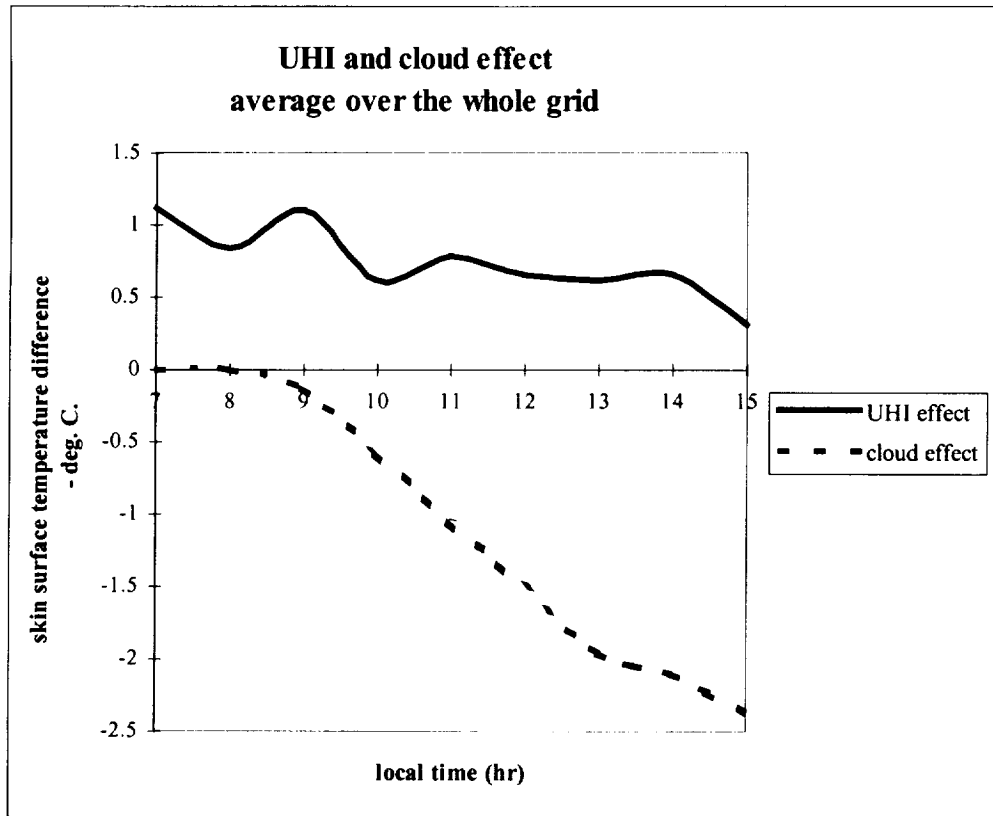


Figure 11. The averaged values of the urban heat island effect and the cloud effect (all °C) on the skin surface temperature, for grid 3.

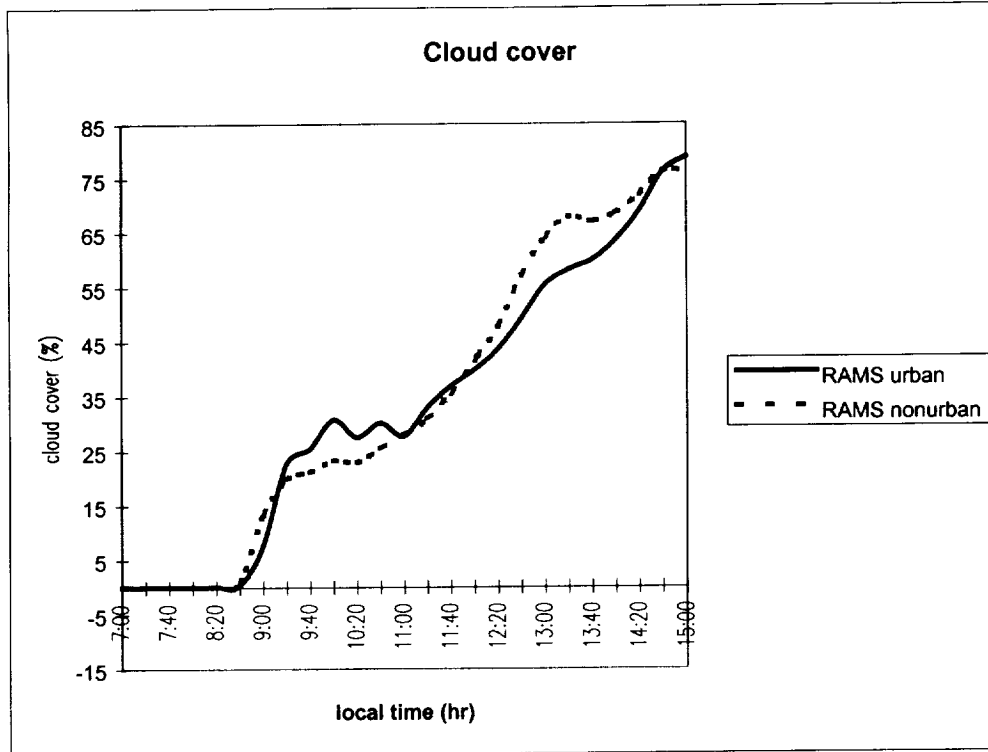


Figure 12. The effect of land use on cloud cover. Comparison of urban and nonurban modeled cloud cover (%) for grid 3.

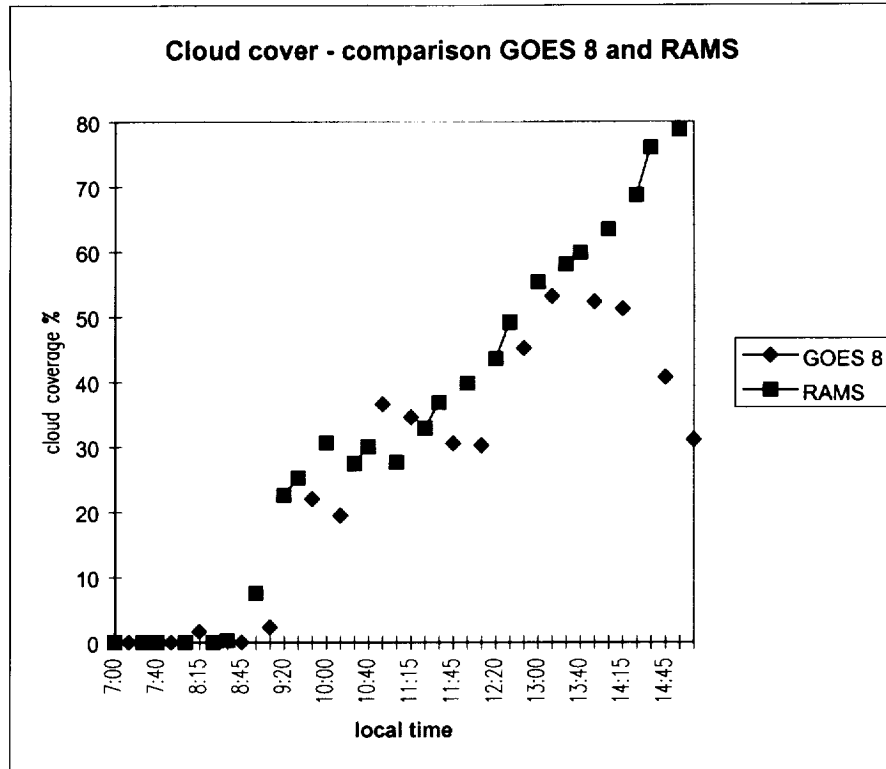


Figure 13. Modeled and observed clouds expressed as cloud coverage (%) for the finest grid 3. [Note that the GOES 8 cloud amounts in this figure were derived by a slightly different algorithm than those in Figure 2 and thus they do not exactly match. Both techniques are experimental and are meant to indicate the relative cloud amount, not its exact value..]

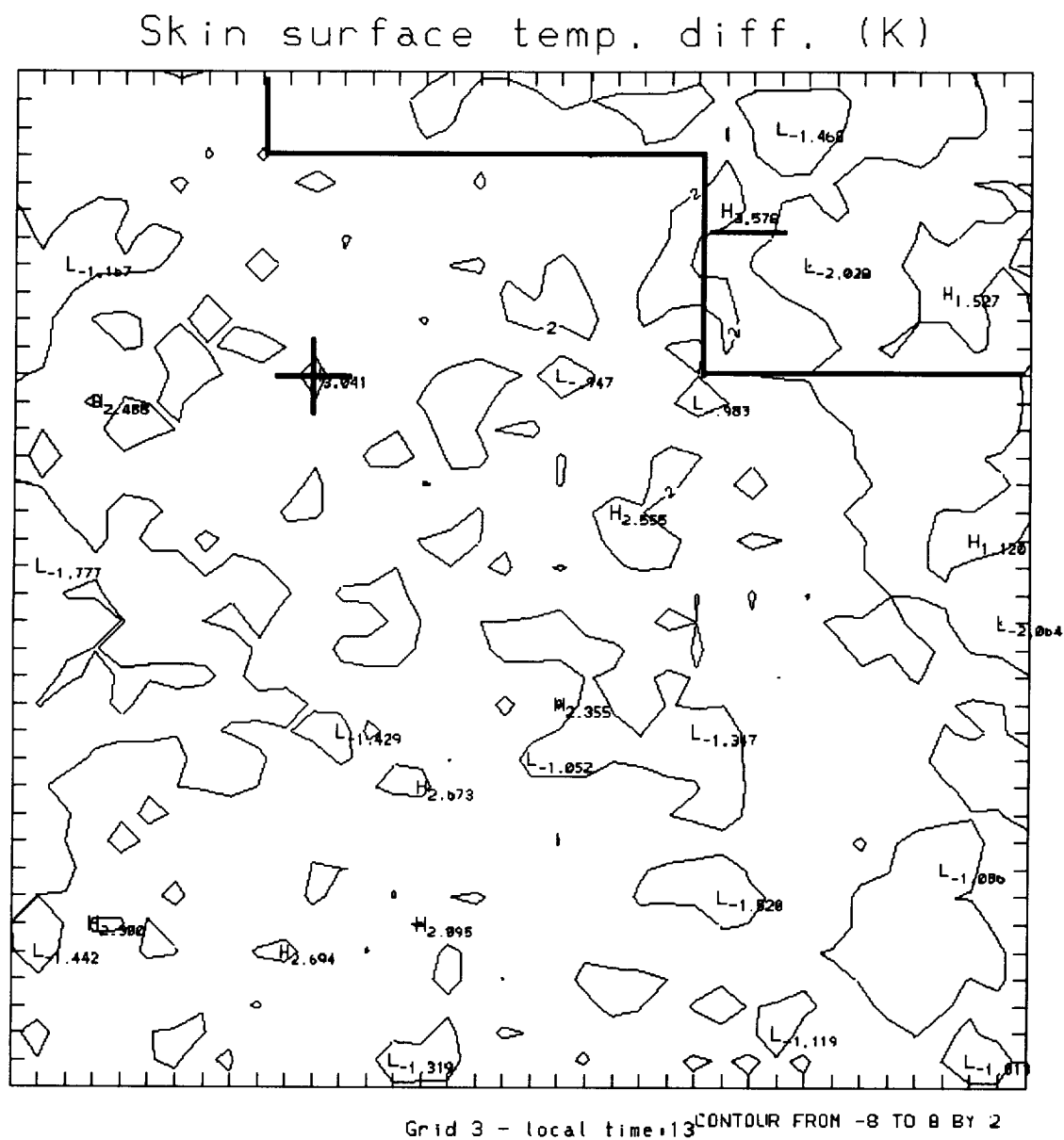


Figure 14 Urban heat island (K) in terms of skin surface temperature at the finest grid 3 at 1300 LST. The thick line marks Atlanta's boundary.

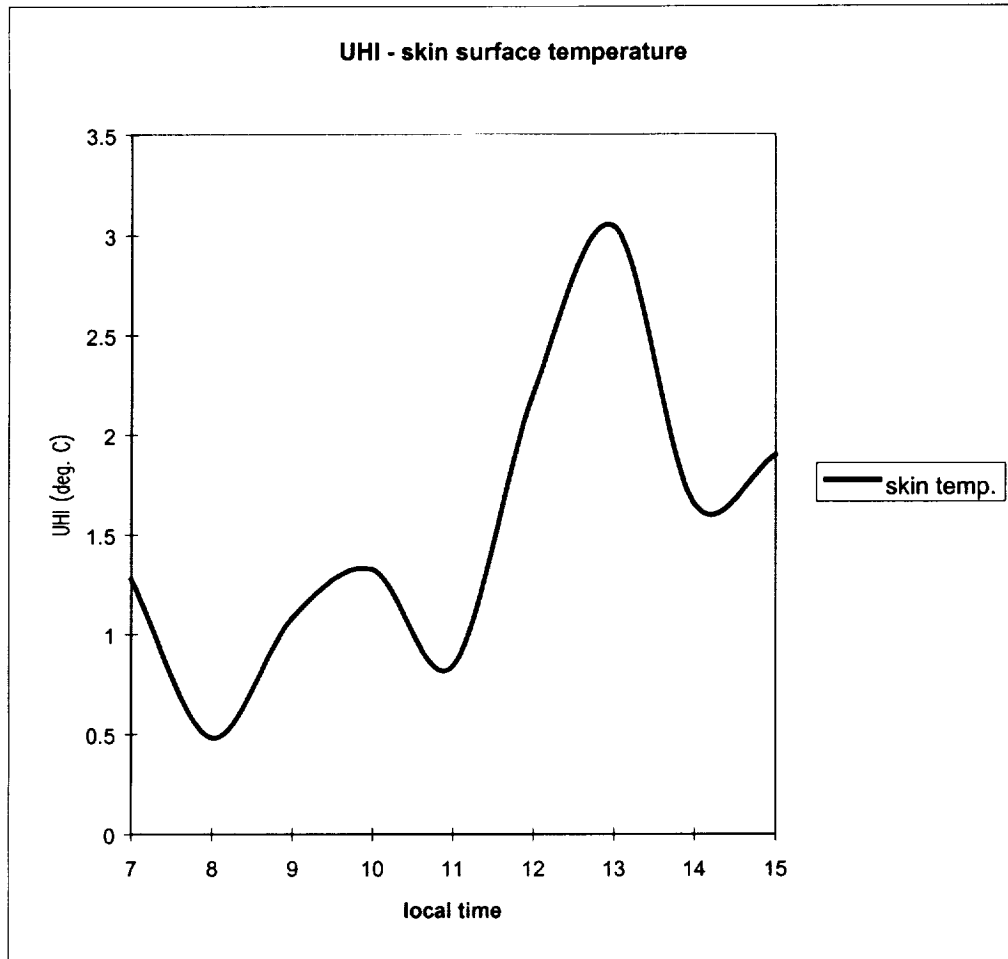


Figure 15. Temporal evolution of the urban heat island ($^{\circ}\text{C}$ skin surface temperature) at the point of its maximum (red cross in Figure 10).

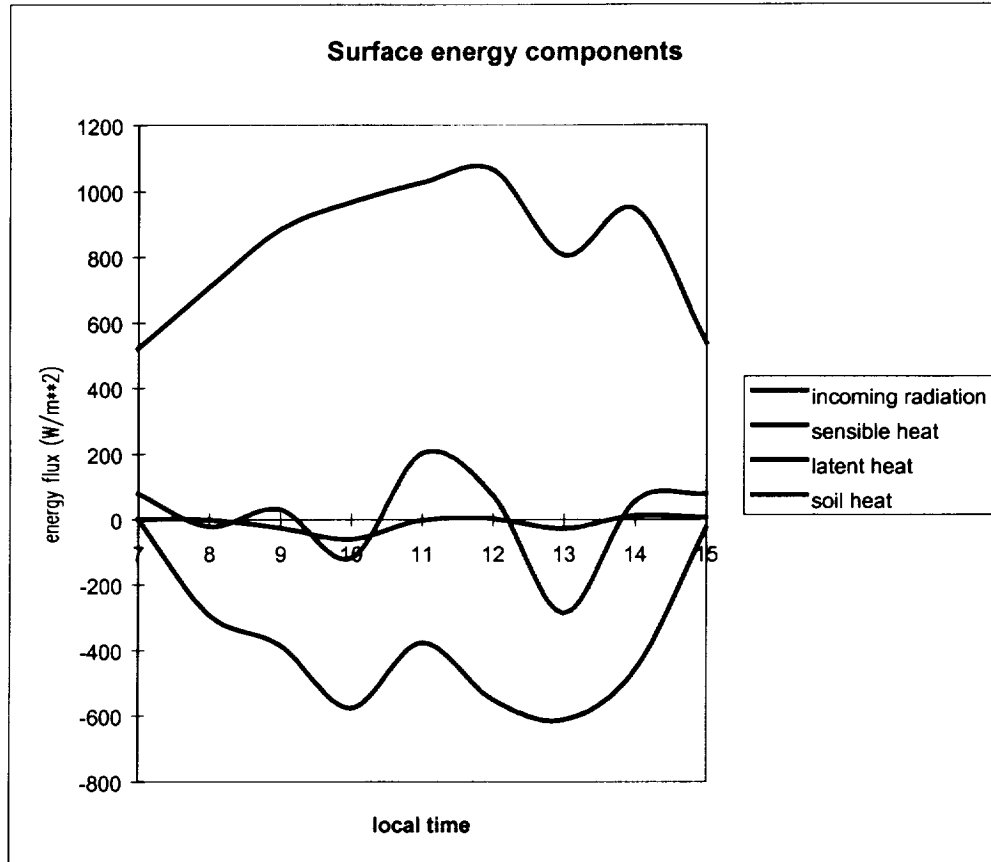


Figure 16. The surface energy components at the point of the maximum magnitude of the urban heat island (red cross in Figure 11).

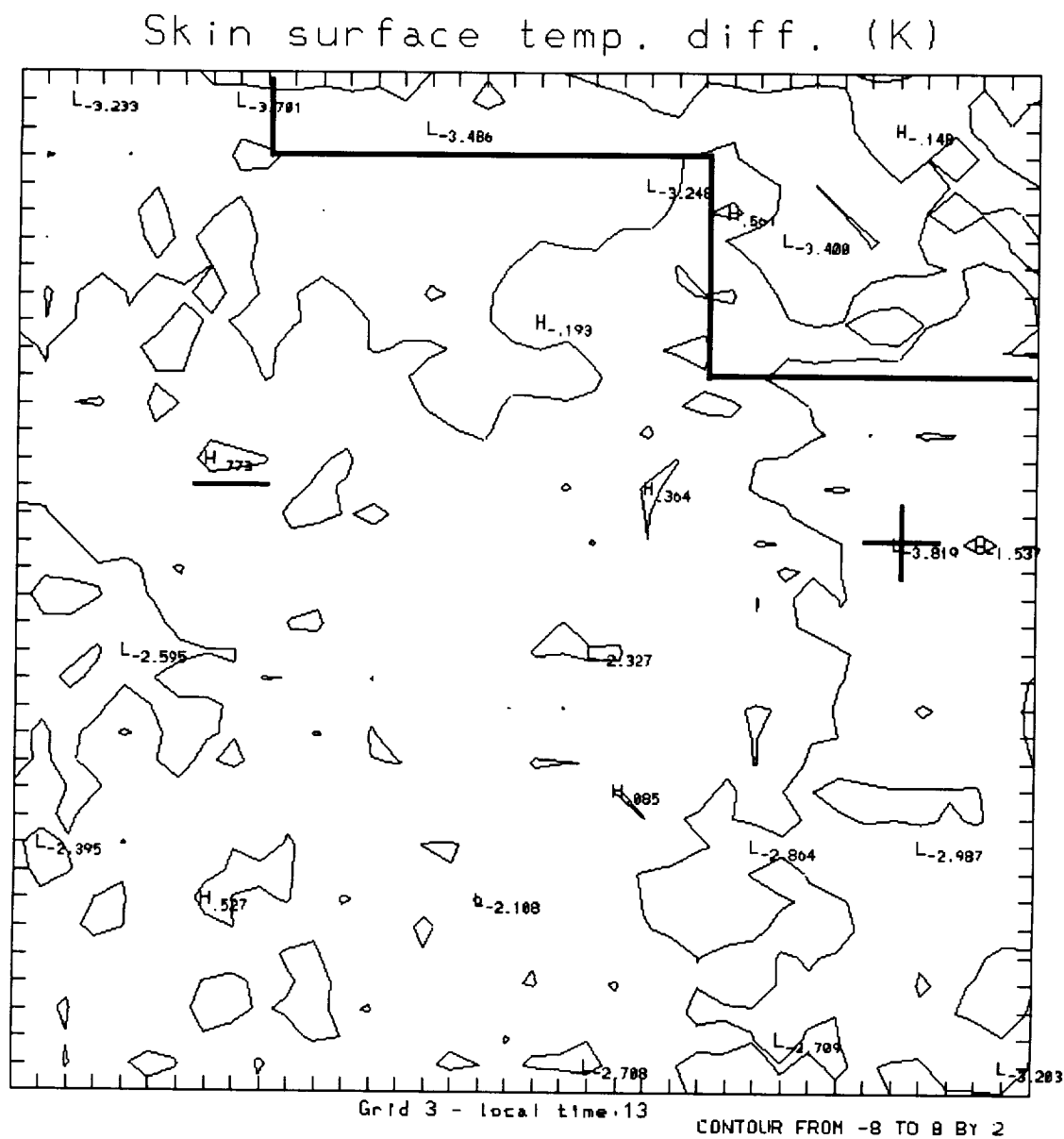


Figure 17. The cloud effect (K) on the skin surface temperature (grid 3). The thick line marks Atlanta's boundary.

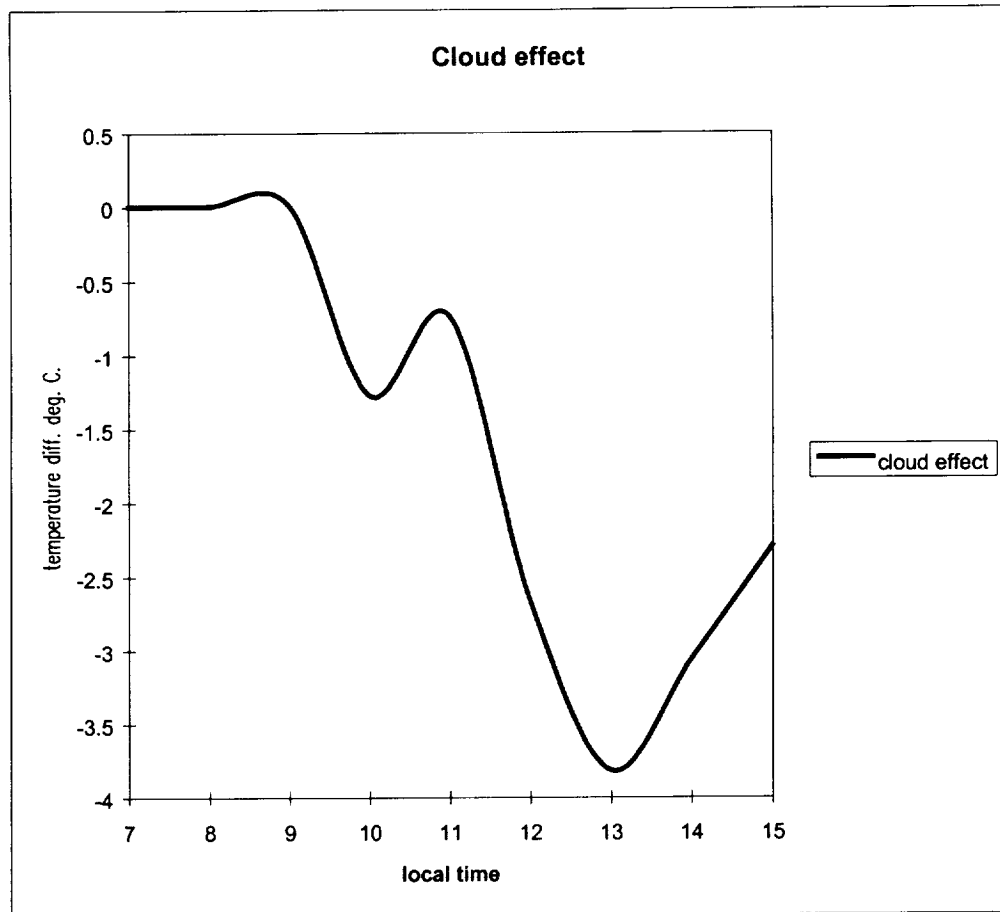


Figure 18. The cloud effect (°C) on the skin surface temperature at the point of its largest magnitude (denoted by the red cross in Figure 13).

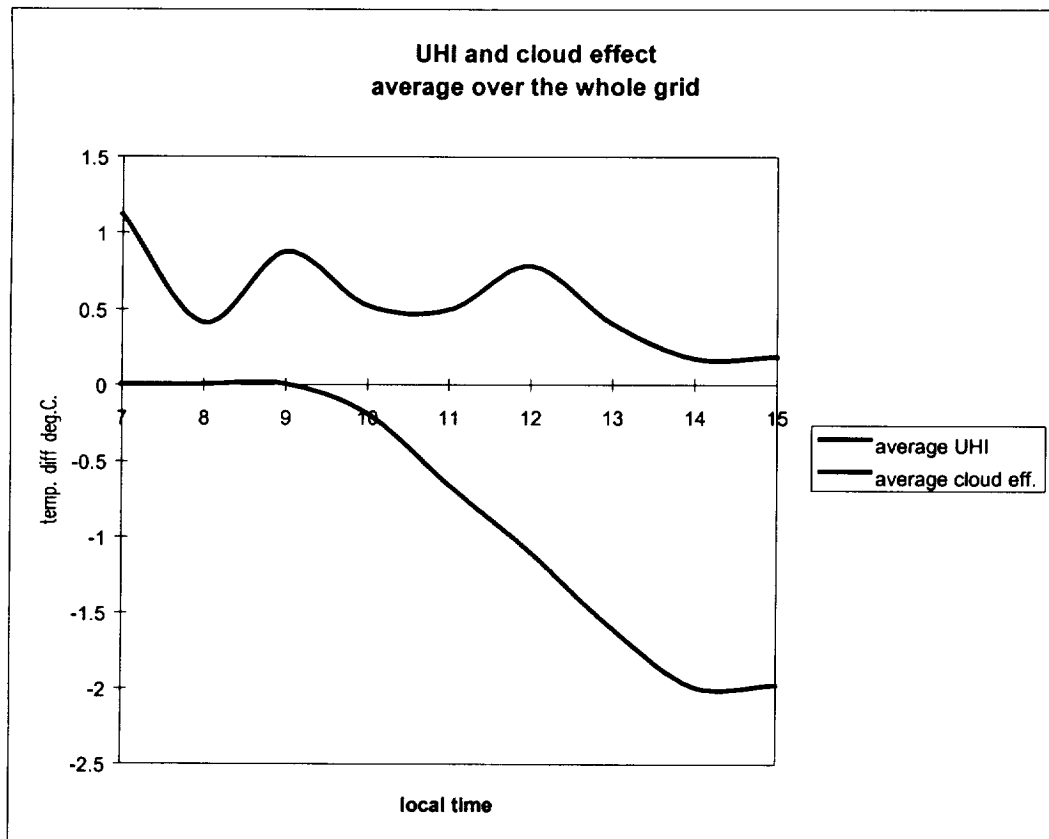


Figure 19. The averaged values of the urban heat island effect and the cloud effect (all °C) on the skin surface temperature, grid 3.

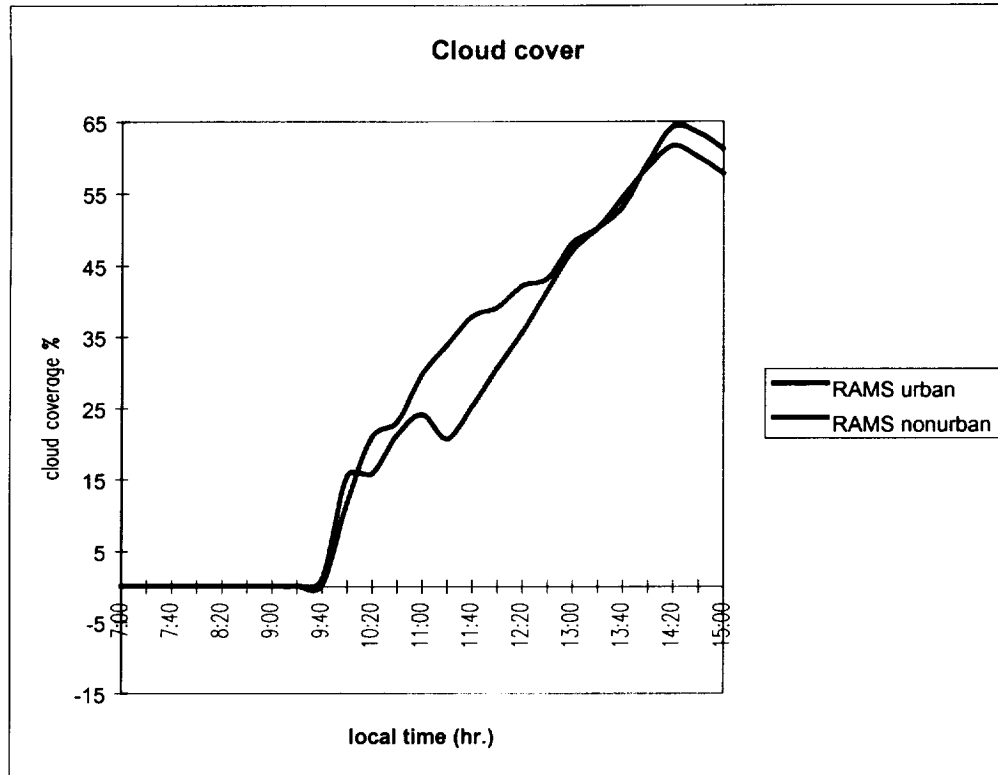


Figure 20. The effect of land use on cloud cover. Comparison of urban and nonurban modeled cloud cover (%) on grid 3.

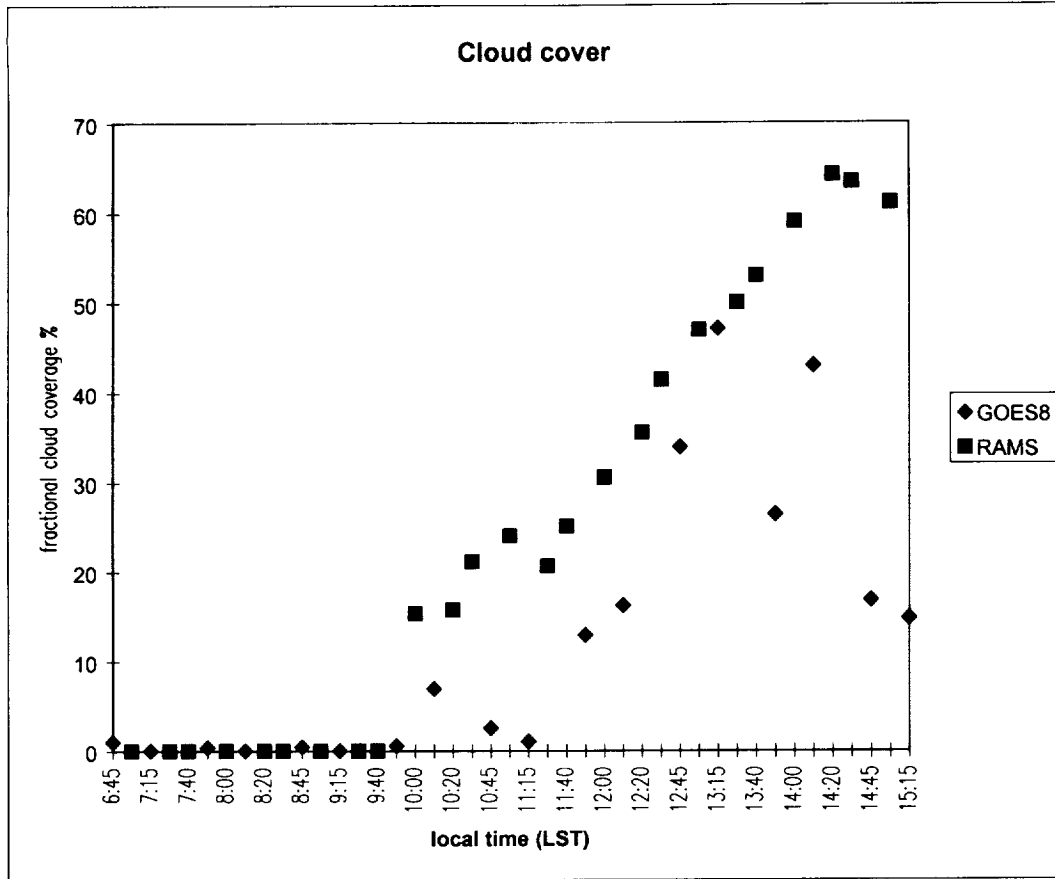


Figure 21. Modeled and observed clouds expressed as the fractional cloud coverage (%) for the finest grid 3.

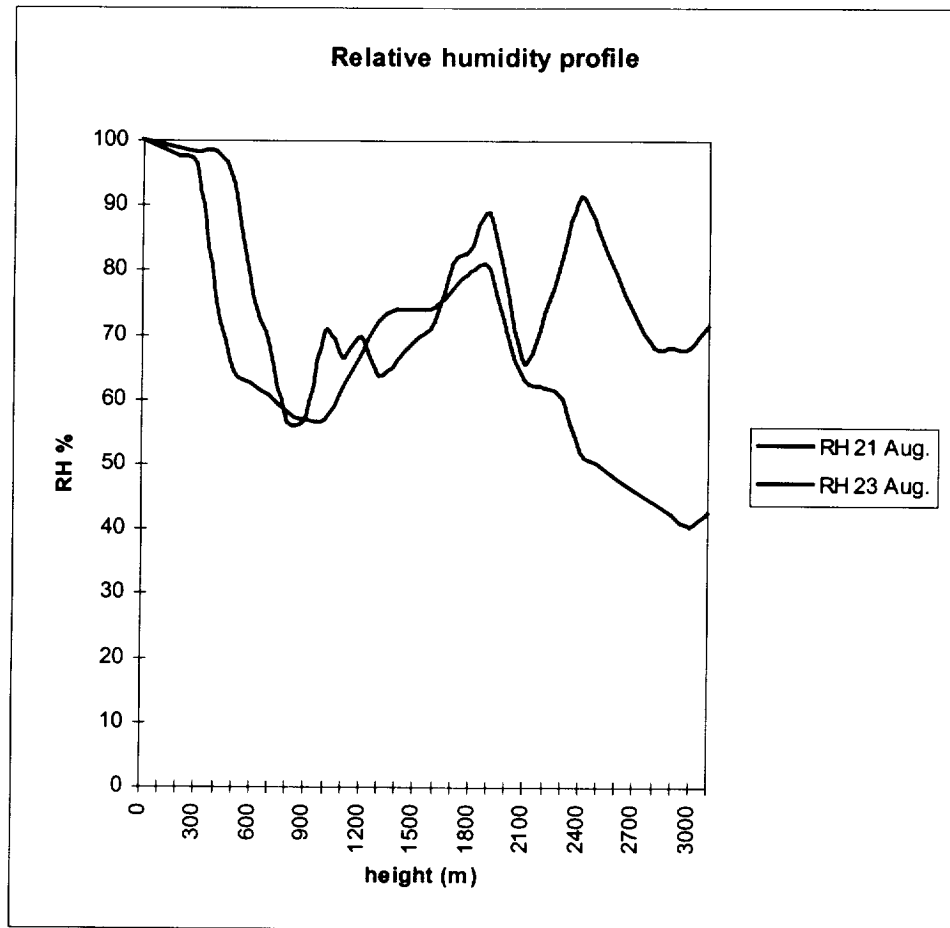


Figure 22. Profiles of relative humidity (%) for 21 and 23 August 1996 12 UTC at Peachtree City.

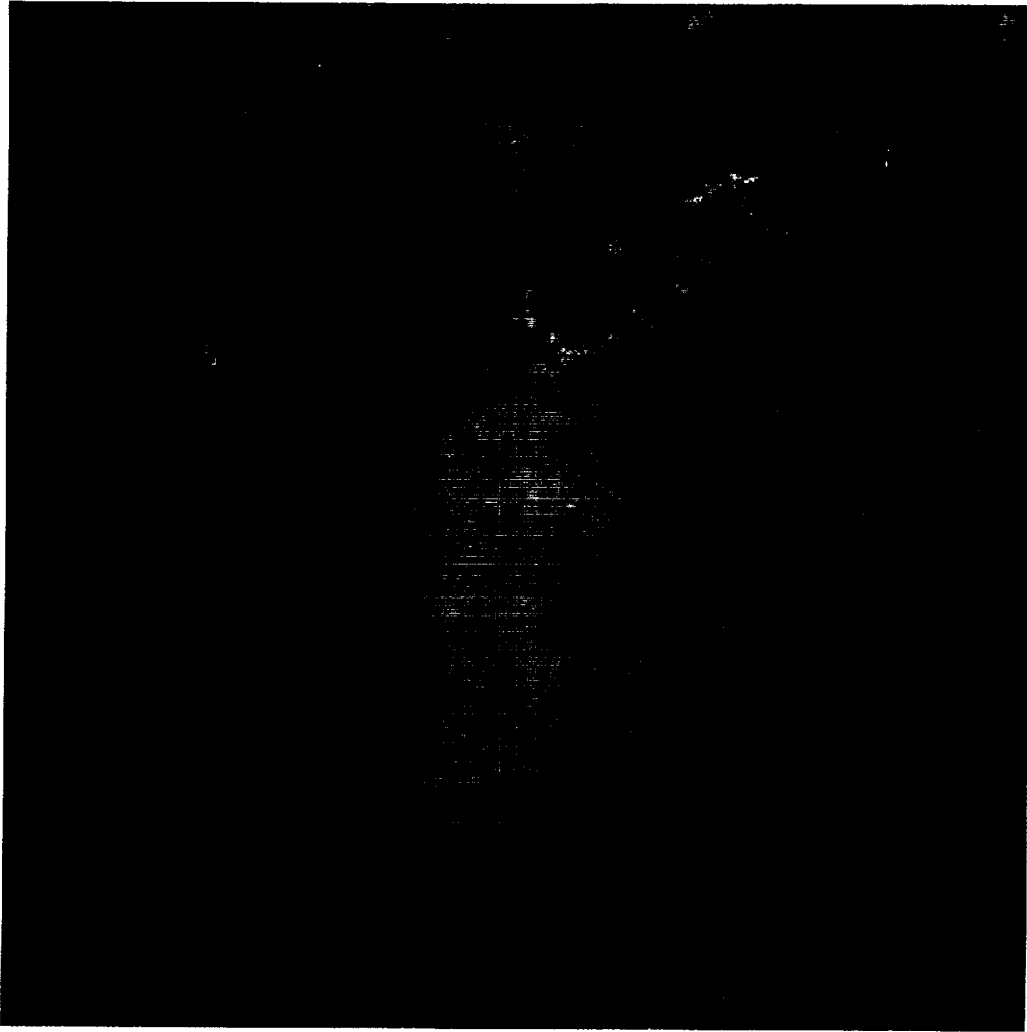


Figure 23a. Fractional cloud cover at 1445 UTC. The city of Atlanta, based on USGS “urban” land use classification, is outlined. Note that the picture is not calibrated but rather proportional to cloud cover. This is since enhancement technique was applied to better show details. The dark pixels correspond to clear sky conditions, bright pixels to cloudy areas.



Figure 23b. Same as Fig. 23a but at 1615 UTC

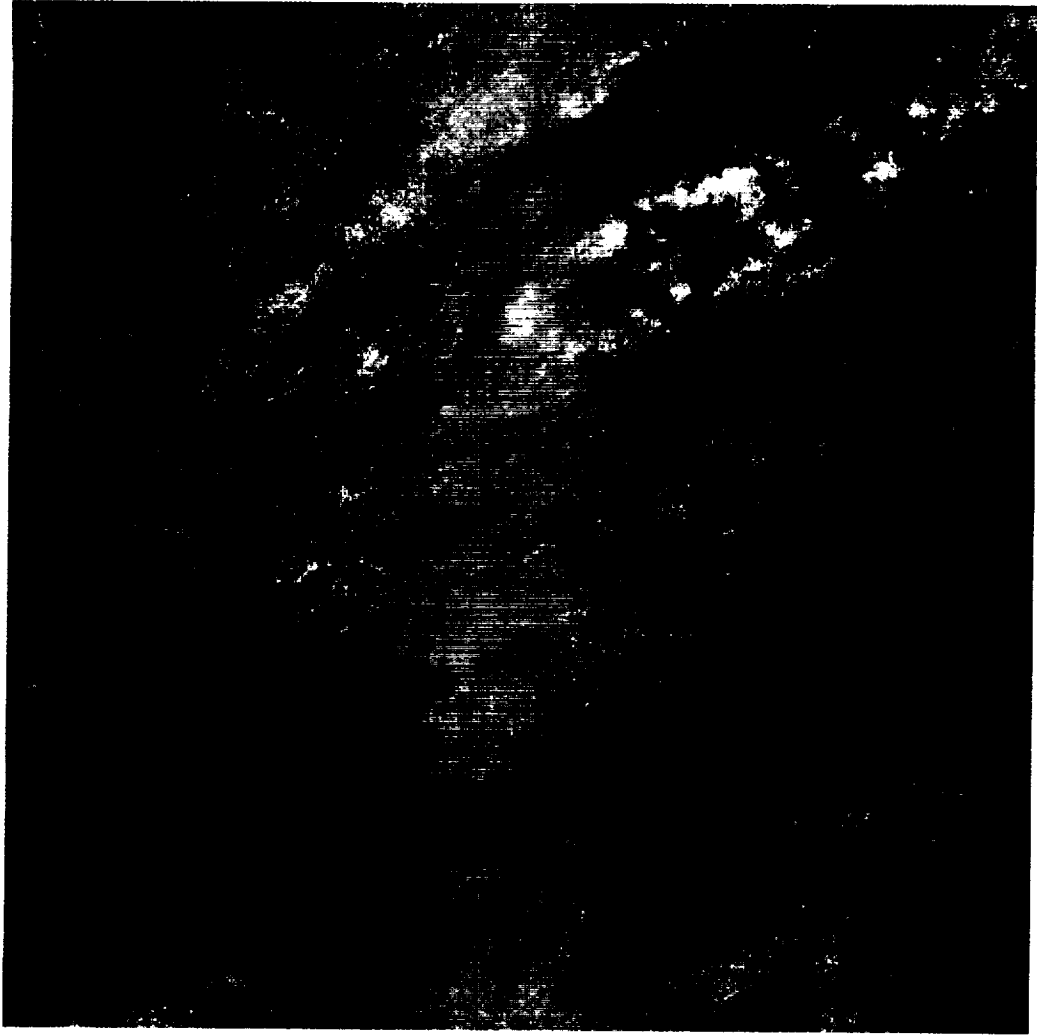


Figure 23c. Same as Fig. 23a but at 1815 UTC.



Figure 23d. Same as Fig. 23a but at 2015 UTC.



Figure 23e. Same as Fig. 23a but at 2115 UTC.



Figure 24a. Enlarged section from Fig. 23b. (corresponding time 1615 UTC).

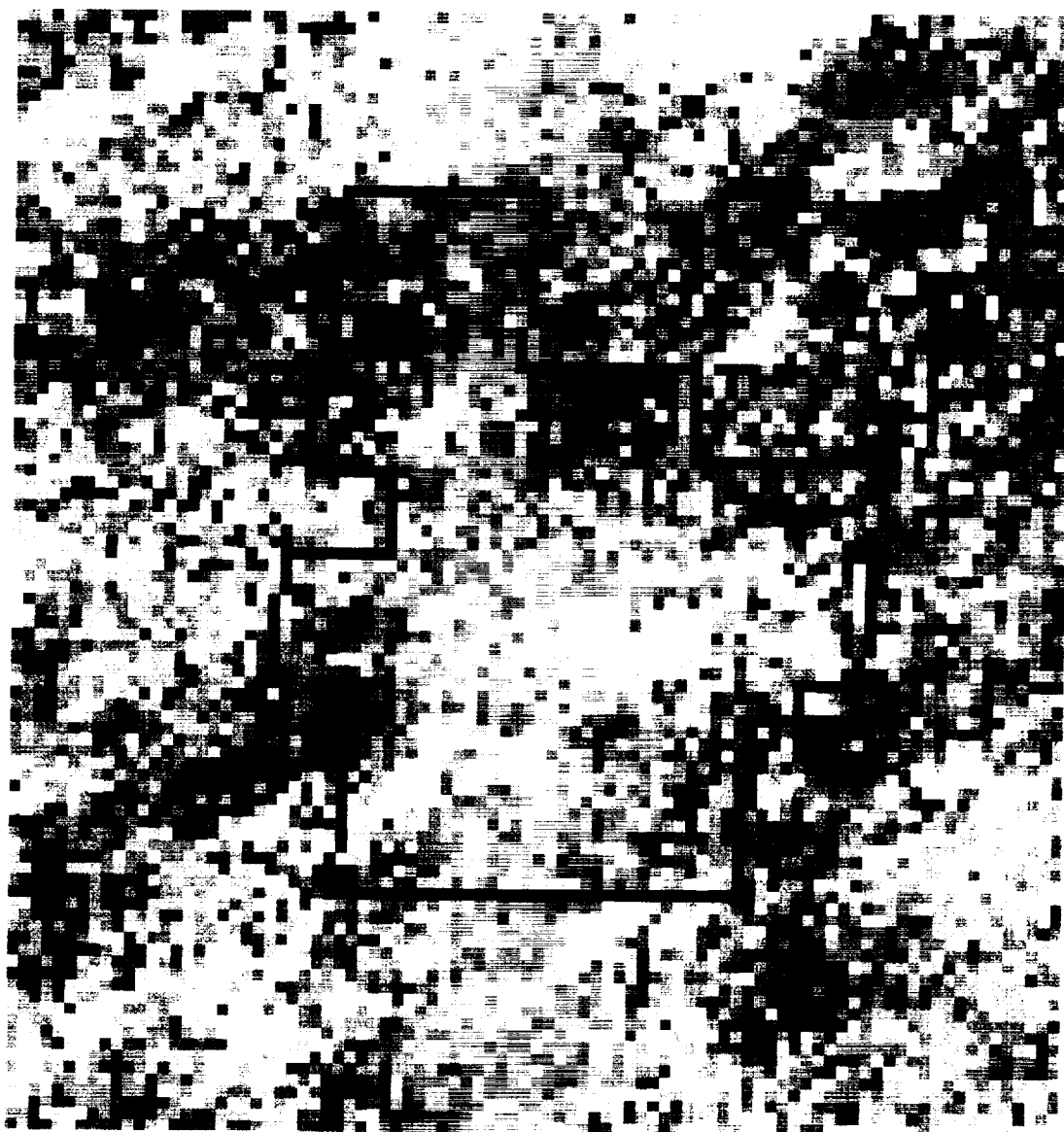


Figure 24b. Enlarged section of Fig. 23c (corresponding time 1815 UTC).



Figure 25a. Cloud cover for the period 15 – 24 August 1996 at 1245 UTC.

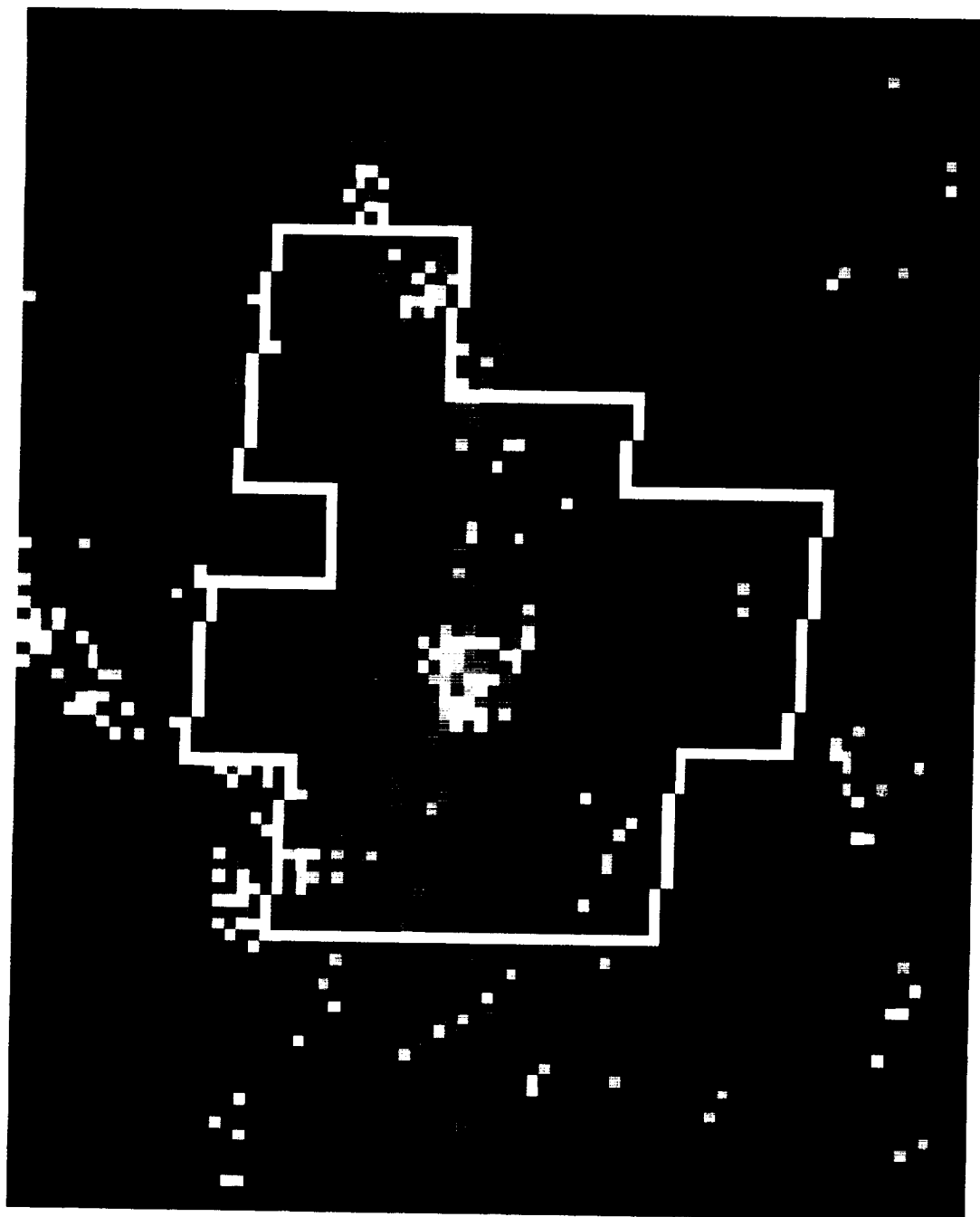


Figure 25b. Enlargement of a section of Fig. 25a.



Figure 26a. Cloud cover for the period 15 – 24 August 1996 at 1745 UTC.

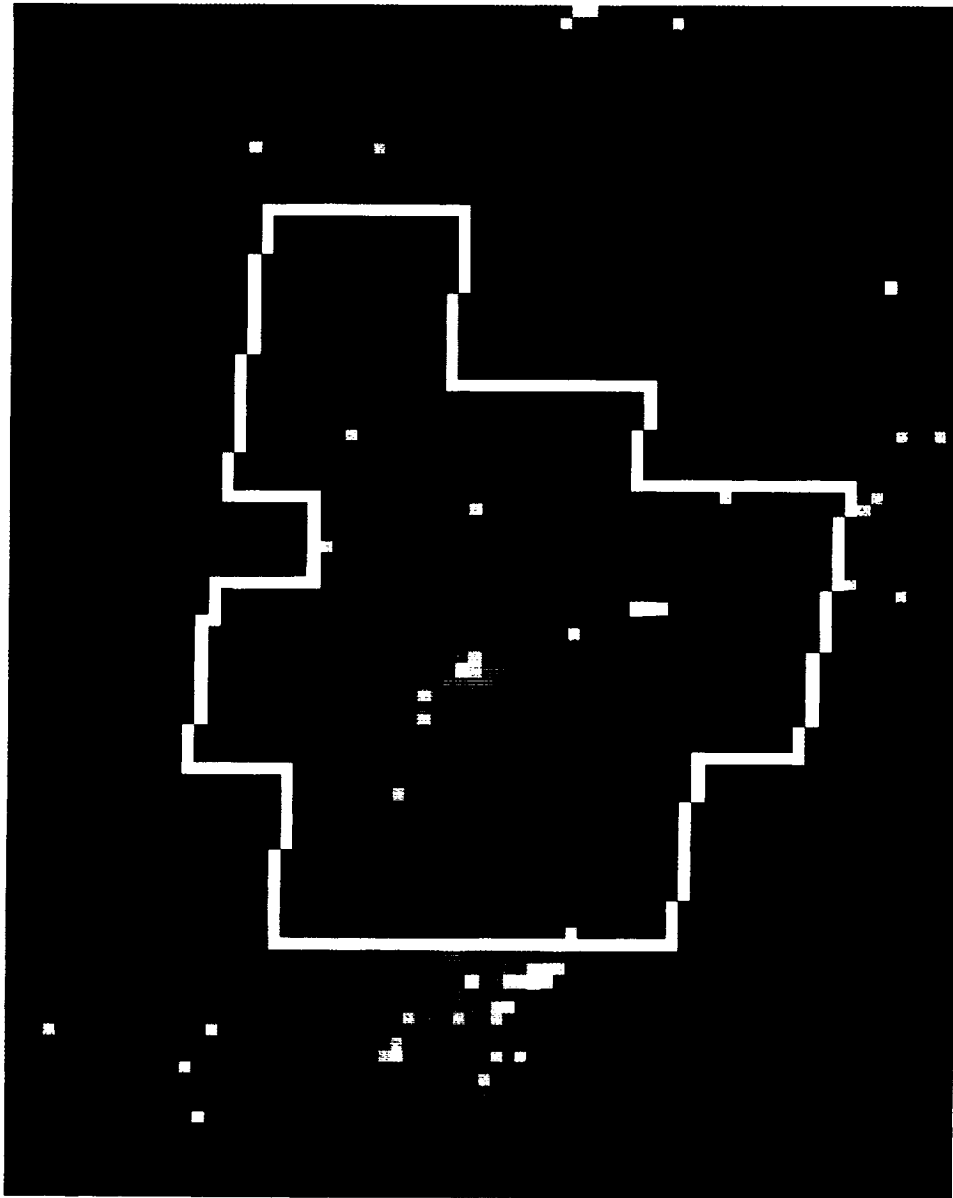


Figure 26b. Enlargement of a section of Fig. 26a.

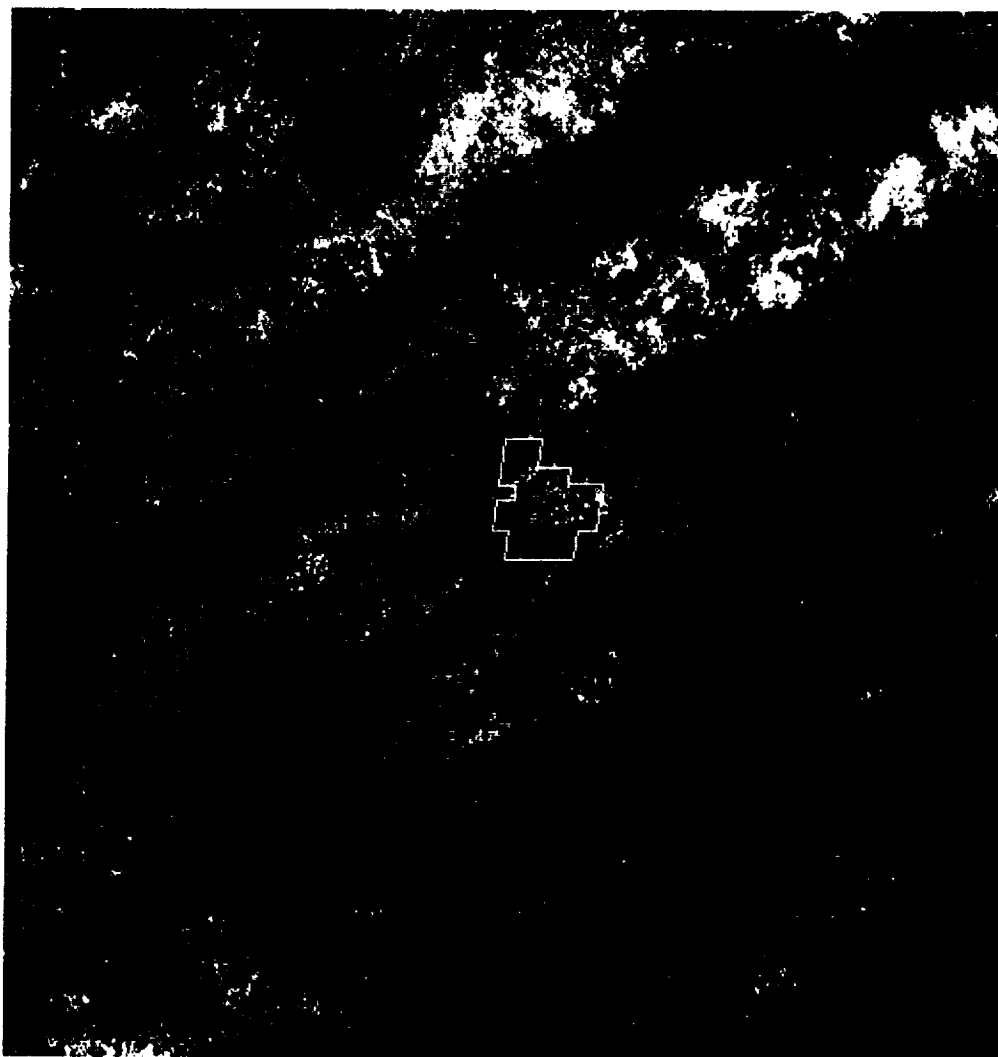


Figure 27a. Cloud cover for the period 15 – 24 August 1996 at 2015 UTC.



Figure 27b. Enlargement of a section of Fig. 27a.

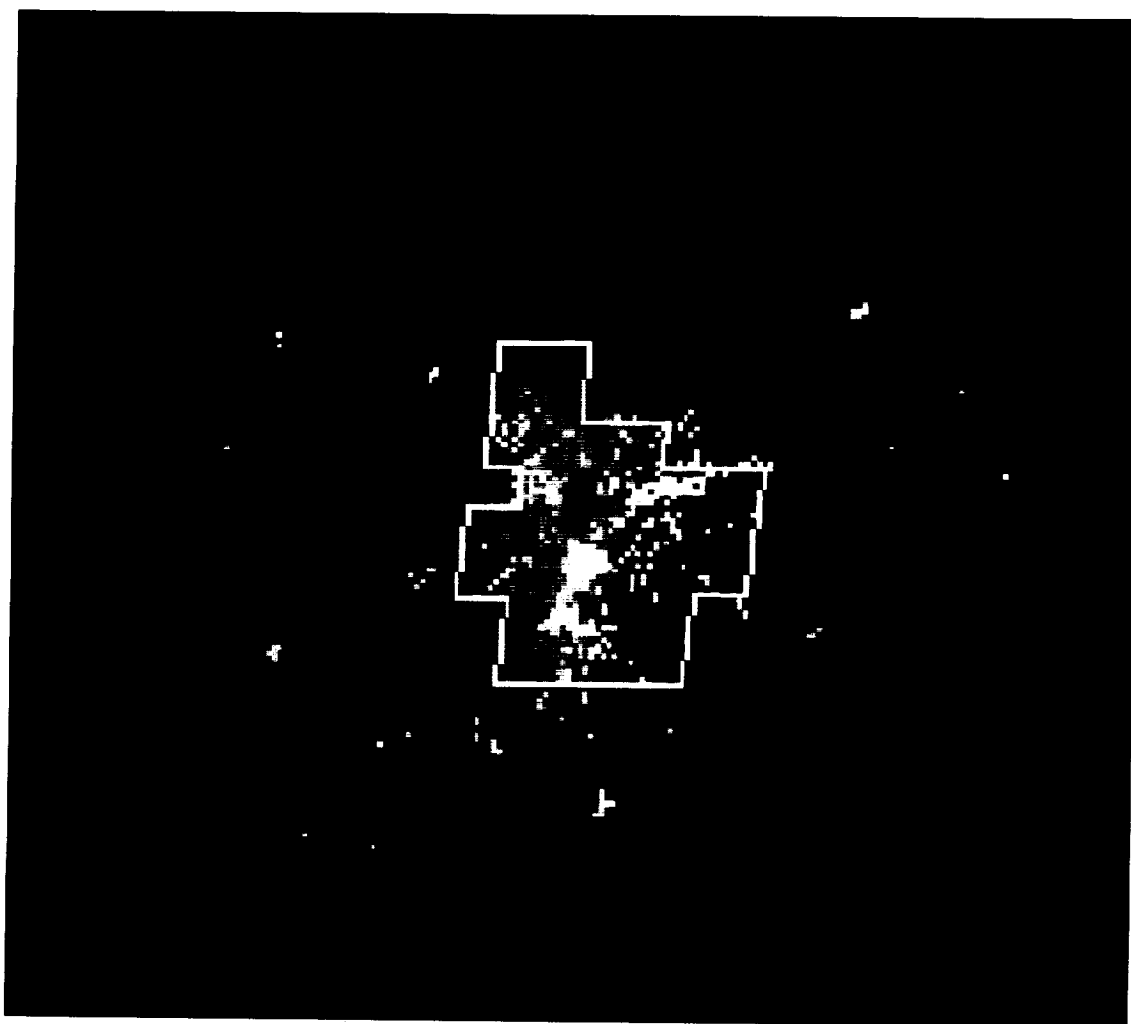


Figure 28. Map of the degree of urbanization based on Landsat TM data. Brighter areas are more urban. The image is in the GOES projection for correlation with GOES-derived clouds. The outline of the USGS Atlanta urban area is shown for comparison. [Data supplied by C. P. Lo, University of Georgia.]

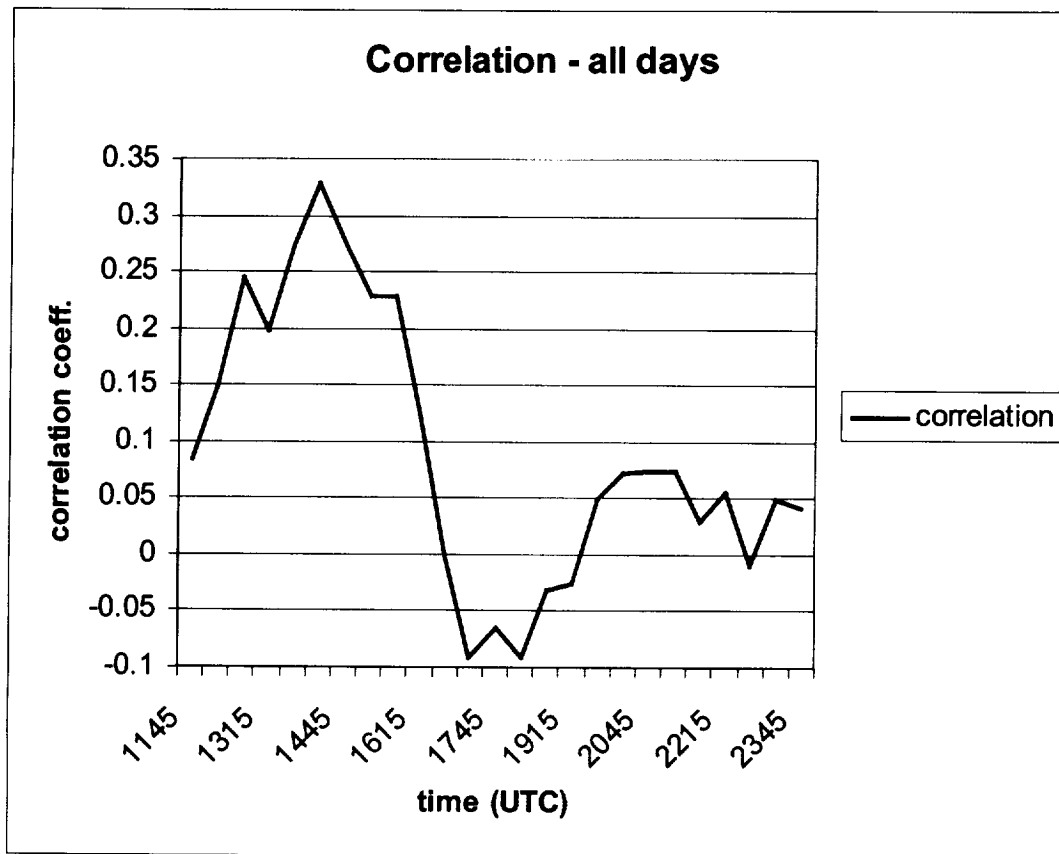


Figure 29a. Correlation coefficients between urban map and cloud climatology (fractional cloud cover) for all 63 days.

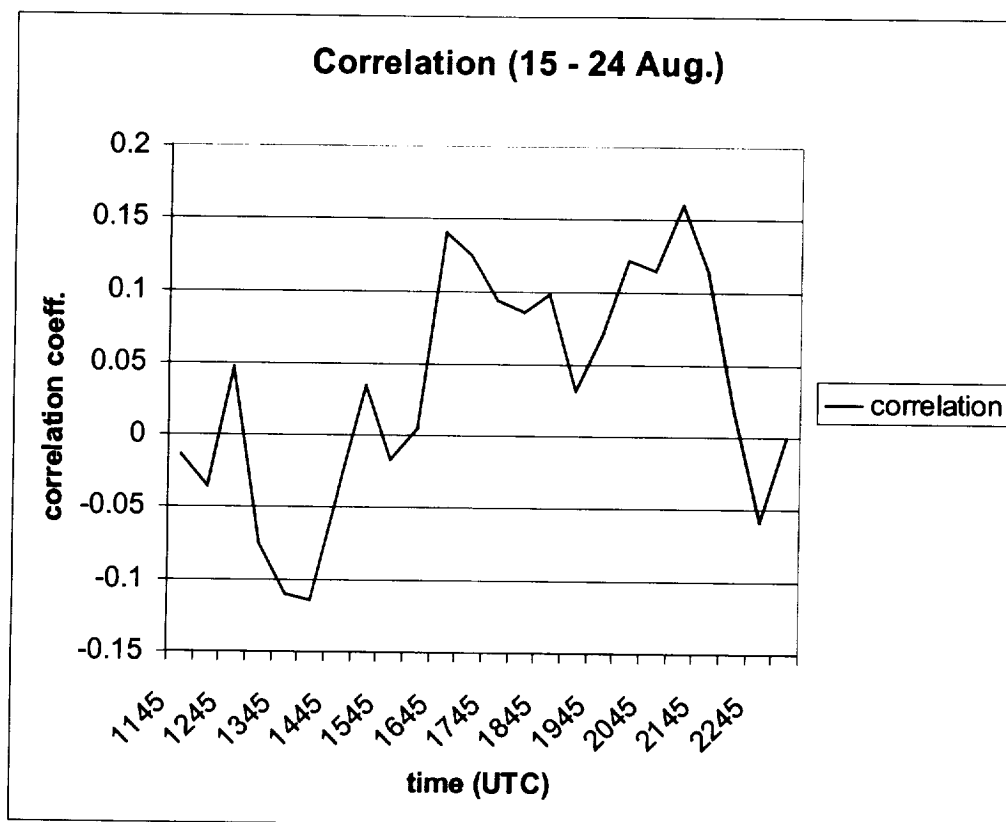


Figure 29b. Same as Fig. 29a, but for calm fair weather conditions (15–24 August 1996).

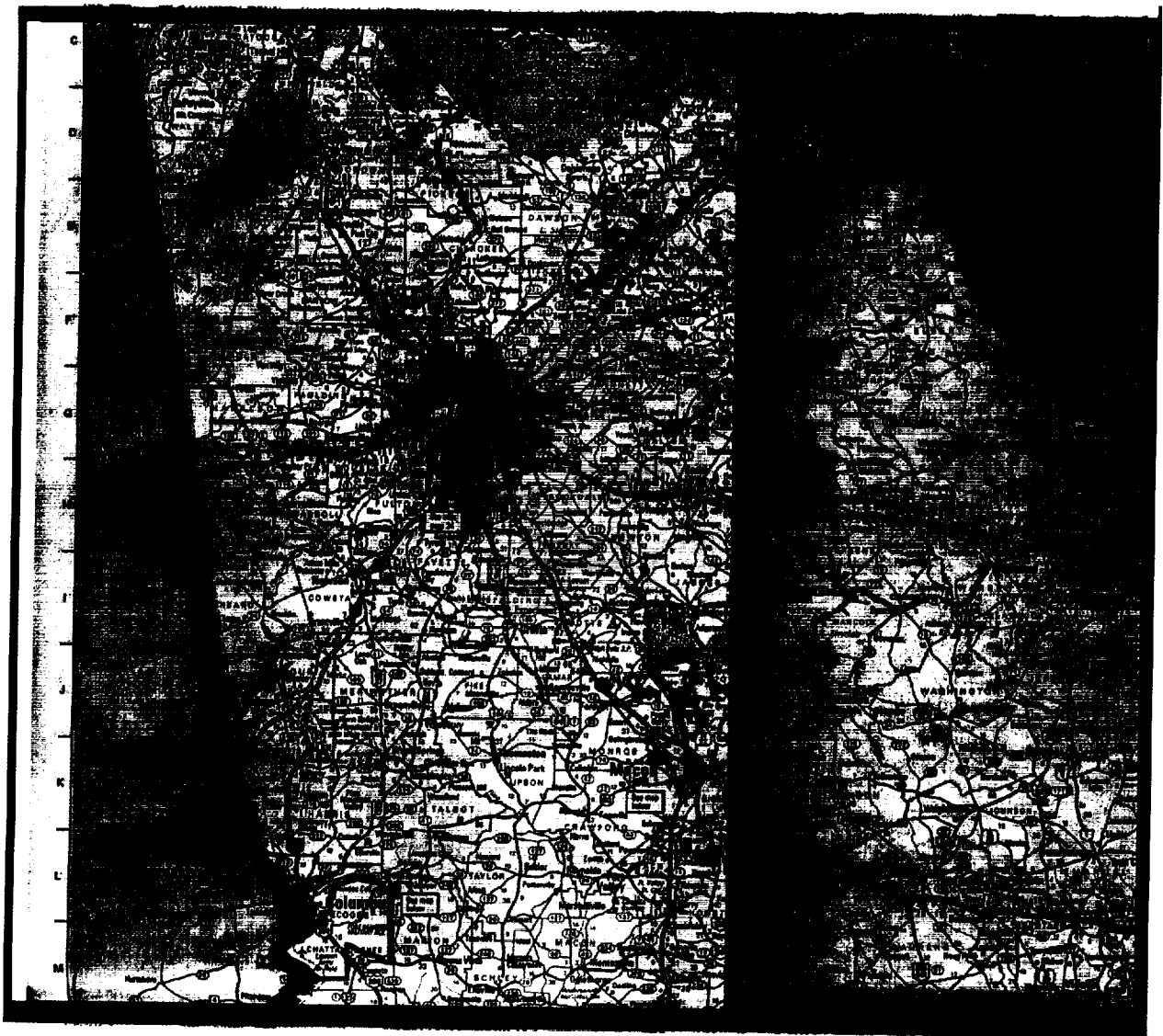


Figure 30. The area covered by grid 1 (the largest grid) in RAMS modeling of the Atlanta region.

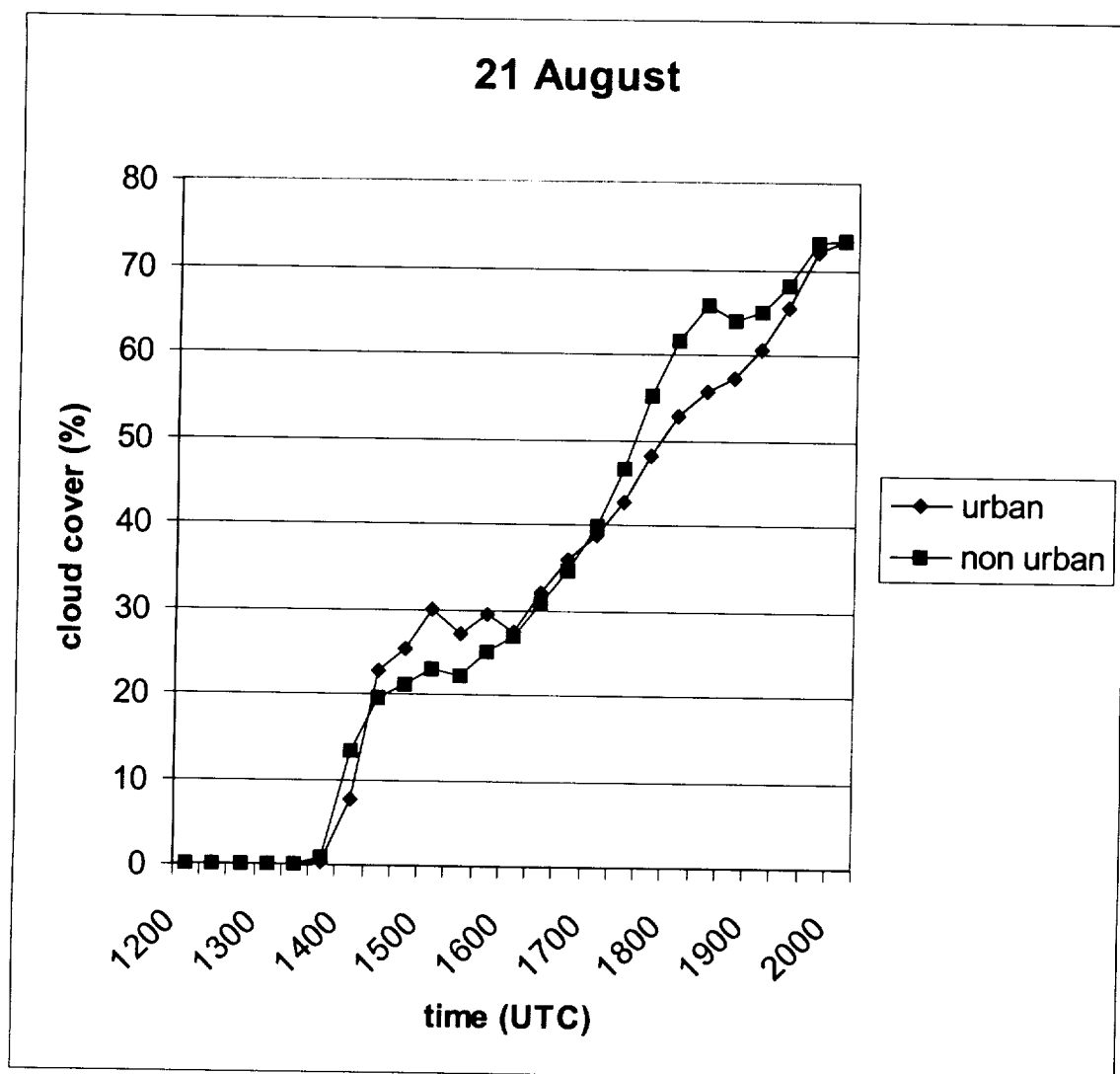


Figure 31a. Fractional cloud cover for urban and nonurban simulations of the Atlanta area on 21 August 1996.

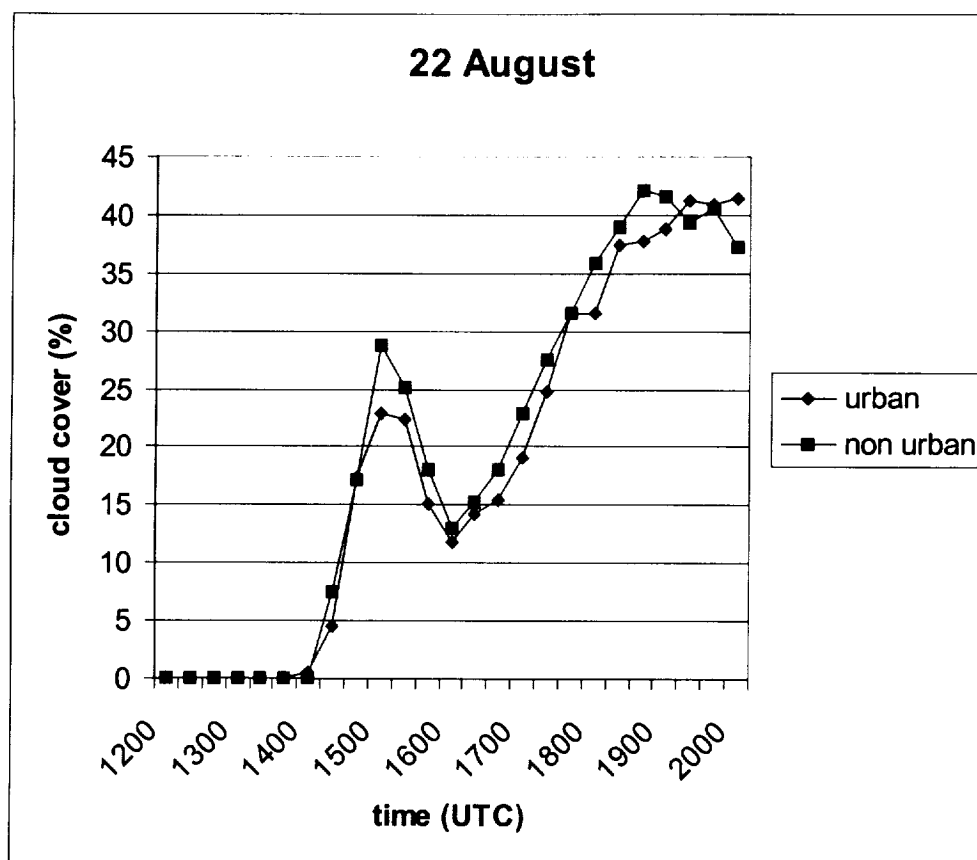


Figure 31b. Same as Fig. 31a but on 22 August 1996.

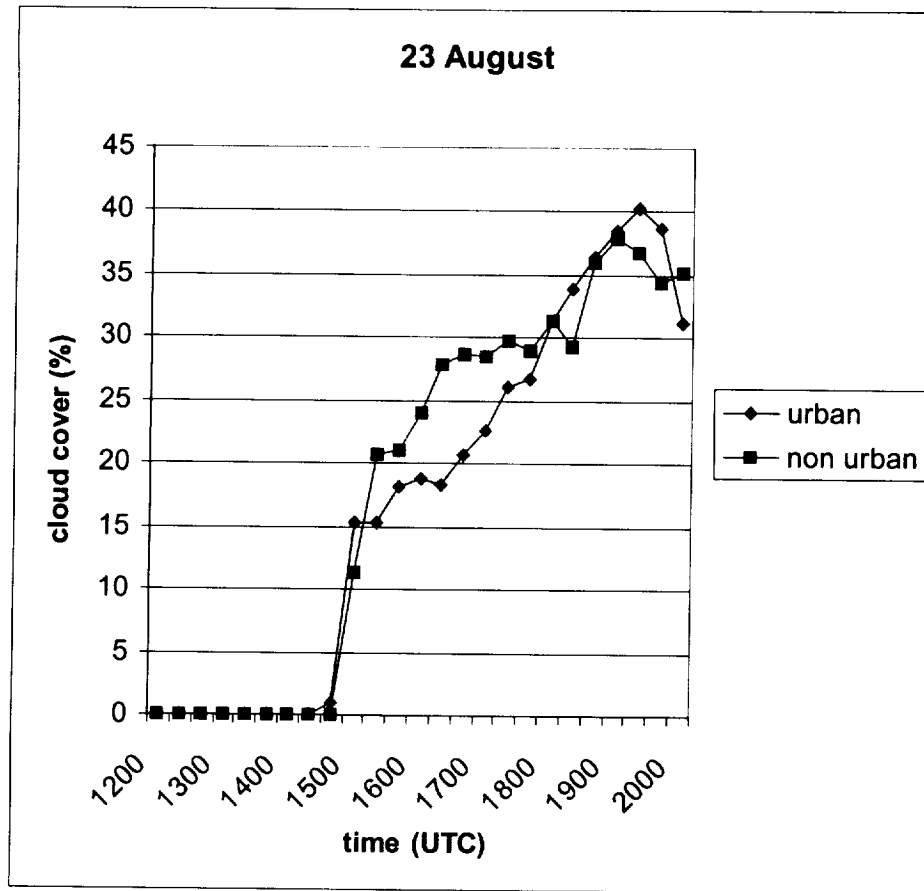


Figure 31c. Same as Fig. 31a but on 23 August 1996.

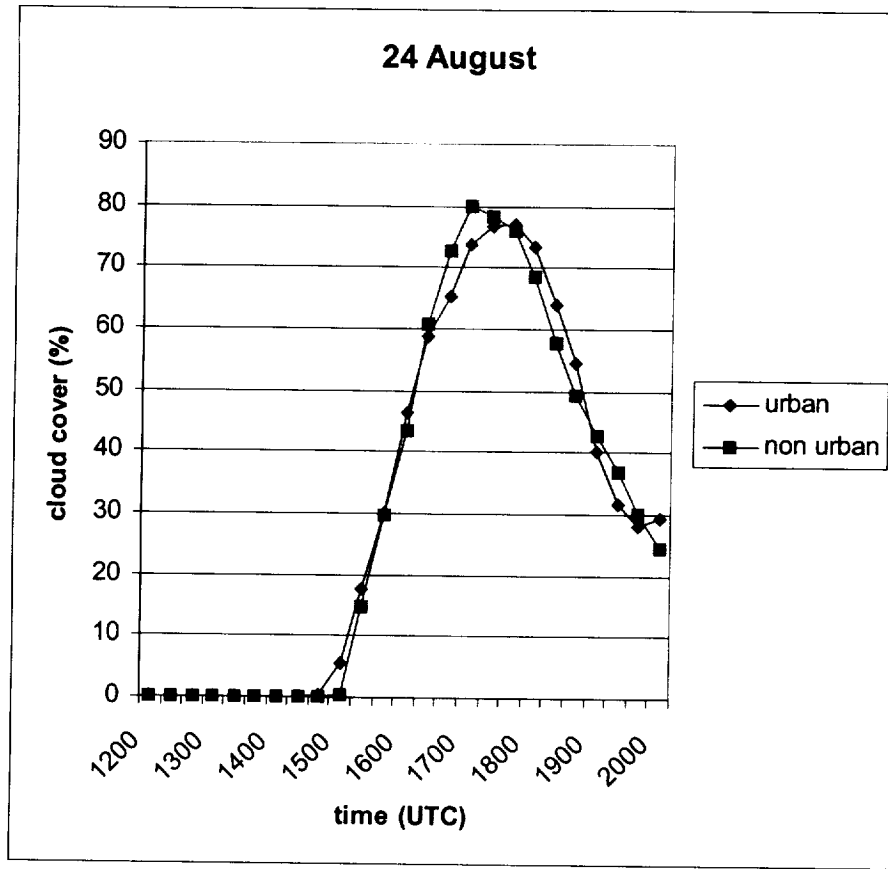


Figure 31d. Same as Fig. 31a but on 24 August 1996.

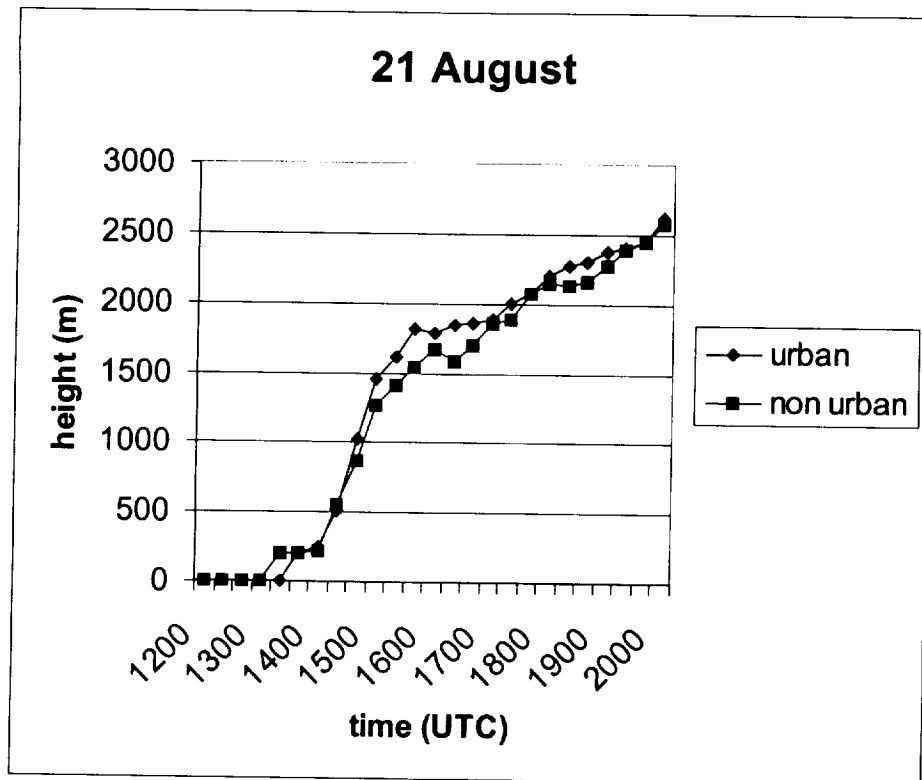


Figure 32a. Cloud base height averaged over the finest grid for urban and nonurban simulation on 21 August 1996.

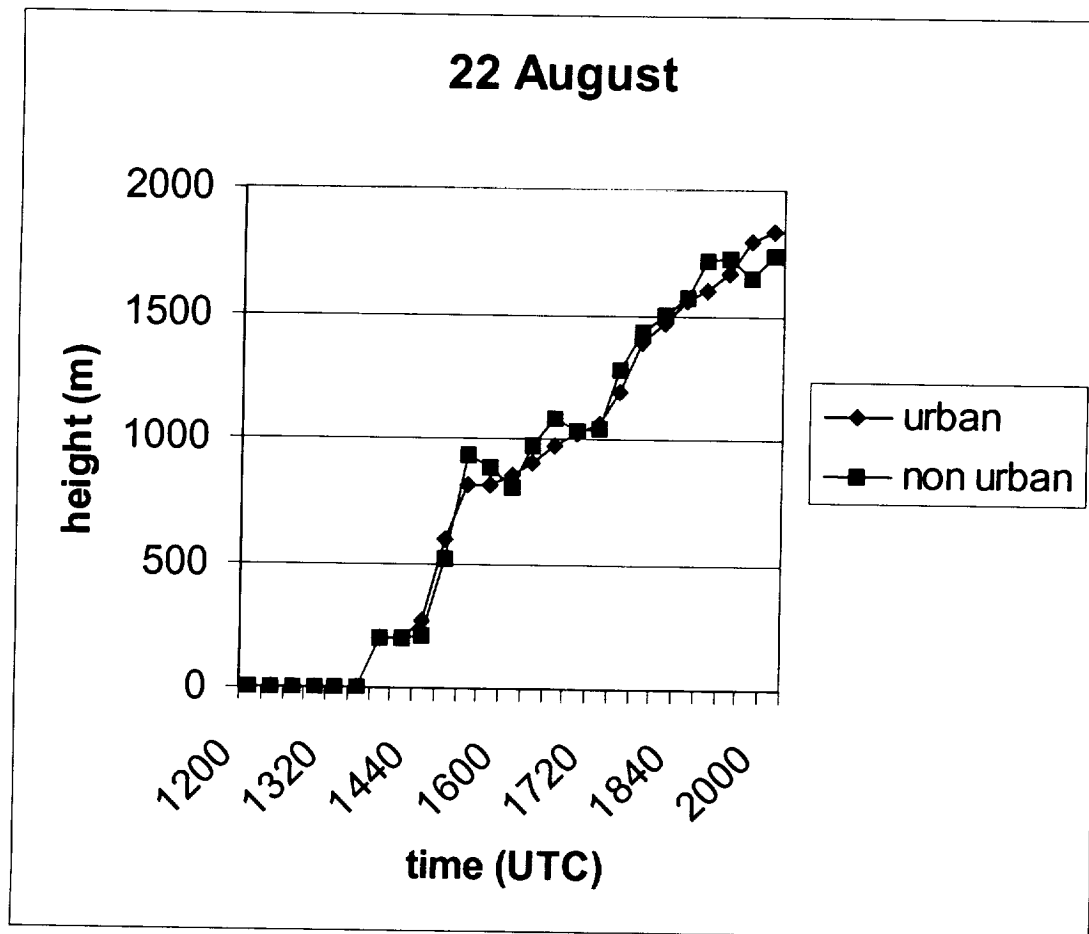


Figure 32b. Same as Fig. 32a but on 22 August 1996.

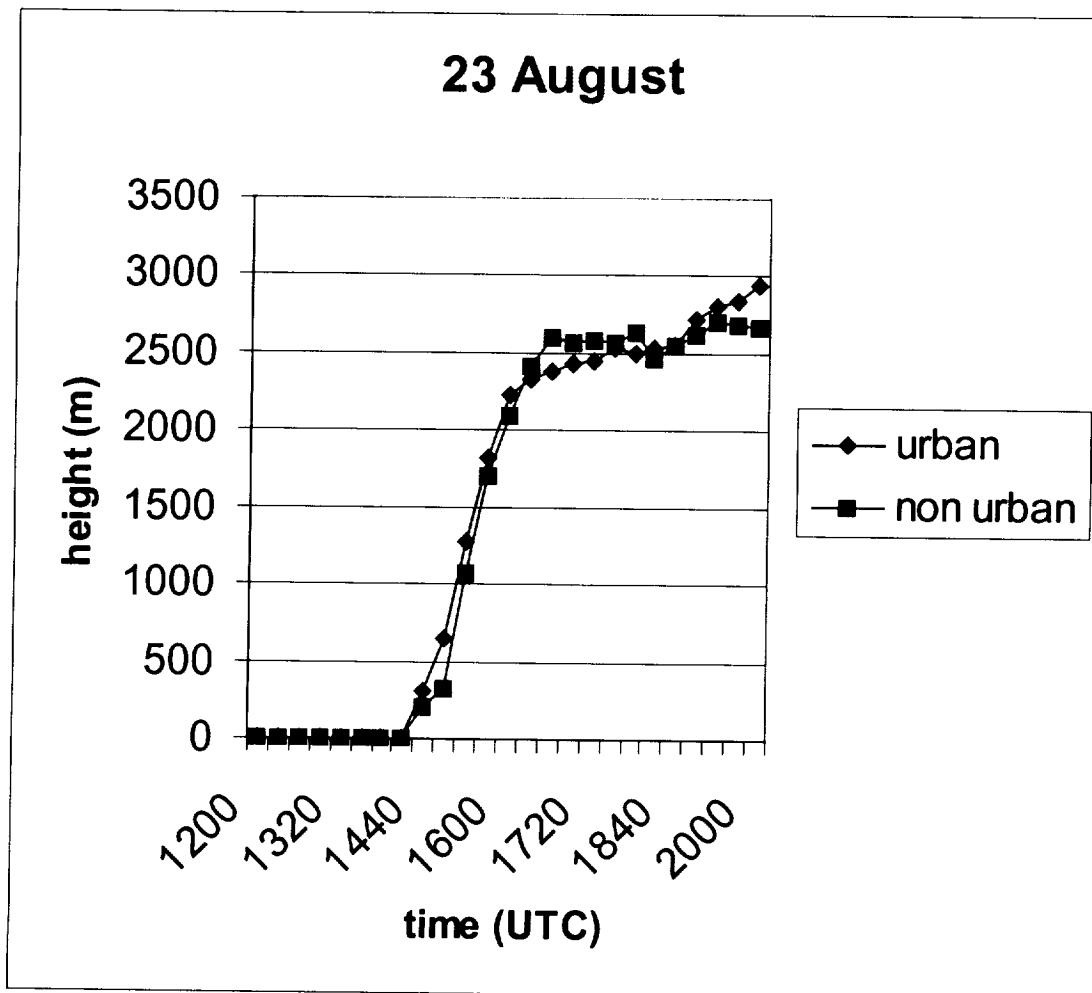


Figure 32c. Same as Fig. 32a but on 23 August 1996.

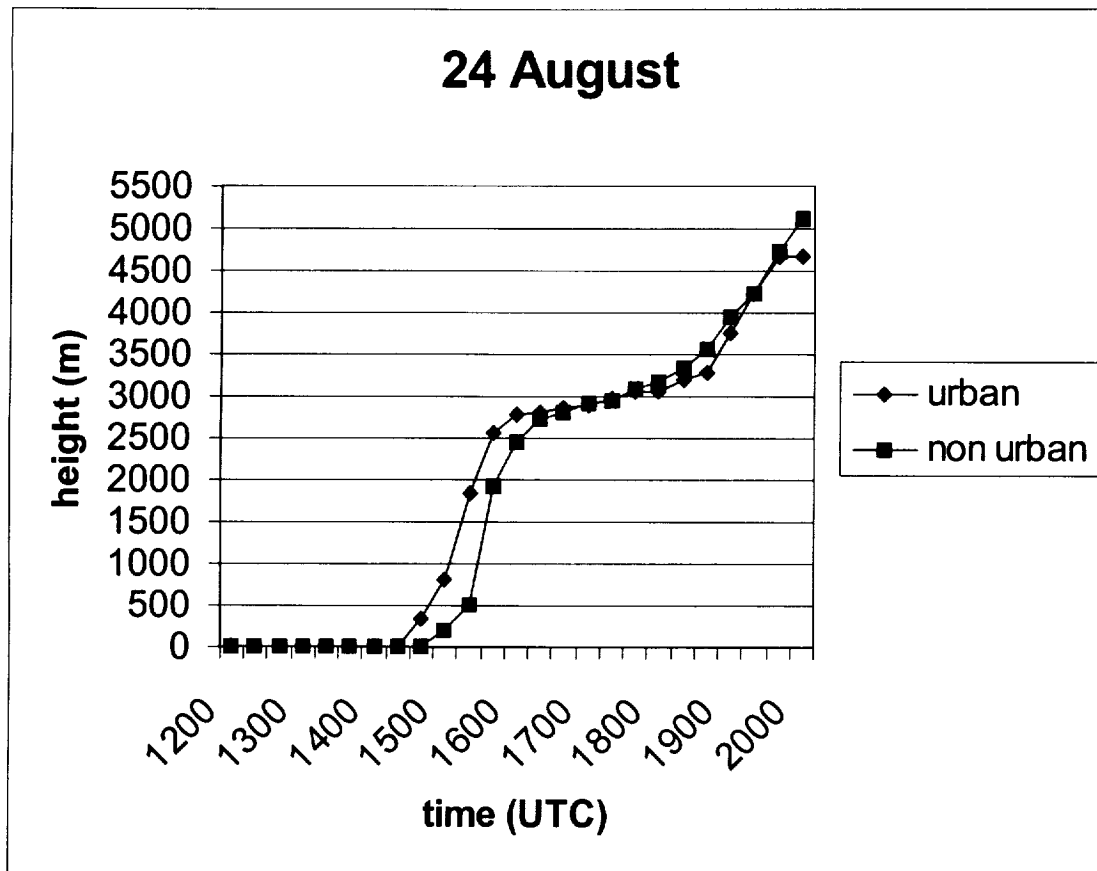


Figure 32d. Same as Fig. 32a but on 24 August 1996.

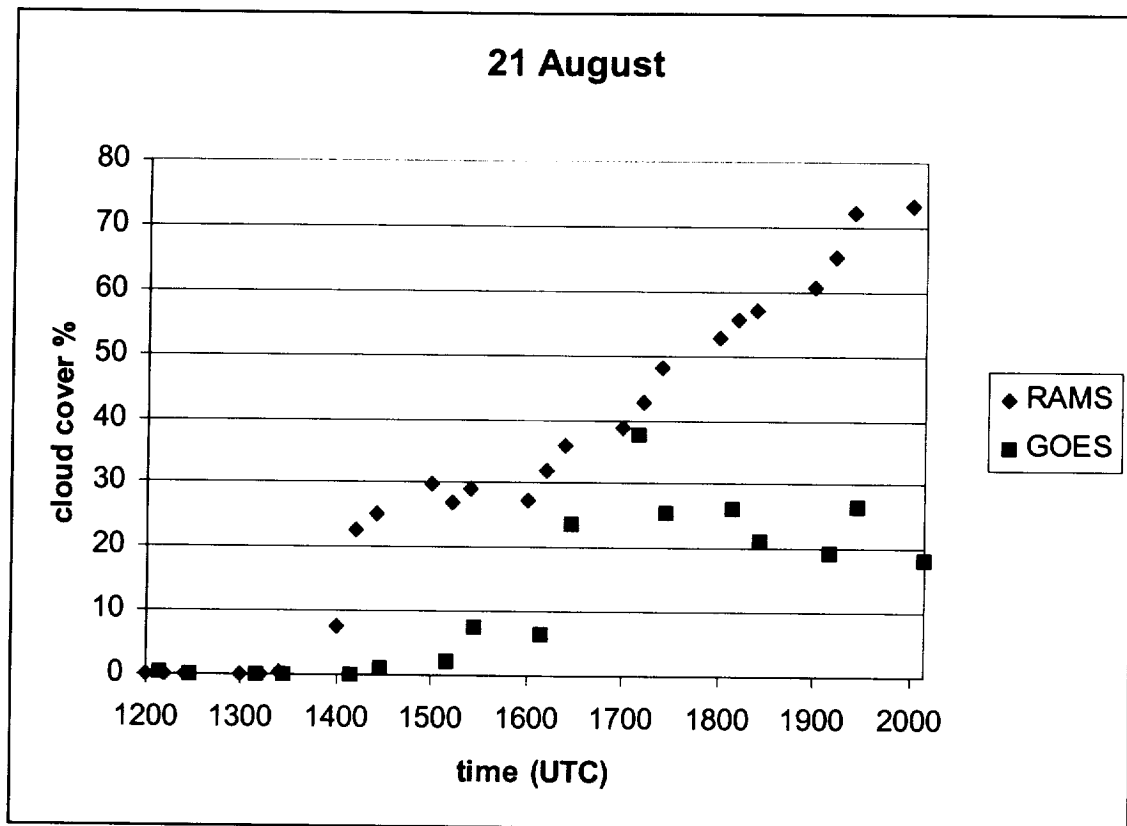


Figure 33a. Comparison of modeled (RAMS) and observed (GOES) cloud cover over the finest grid 3 on 21 August 1996.

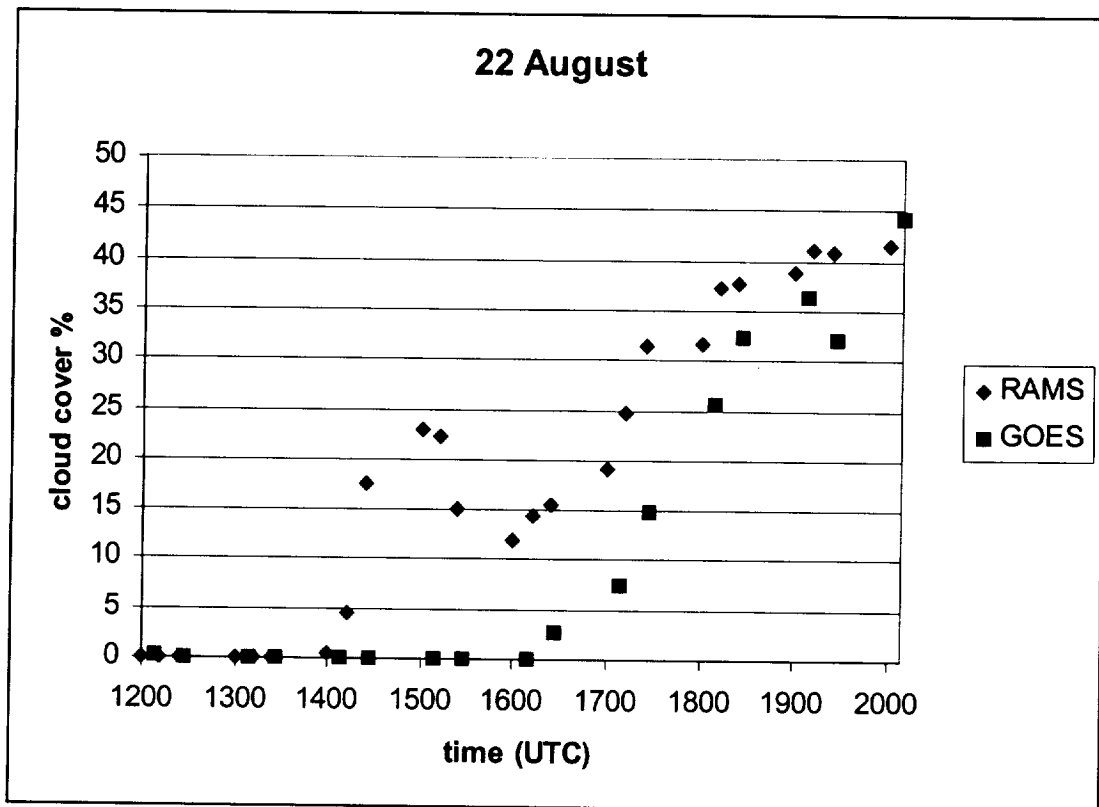


Figure 33b. Same as Fig. 33a but on 22 August 1996.

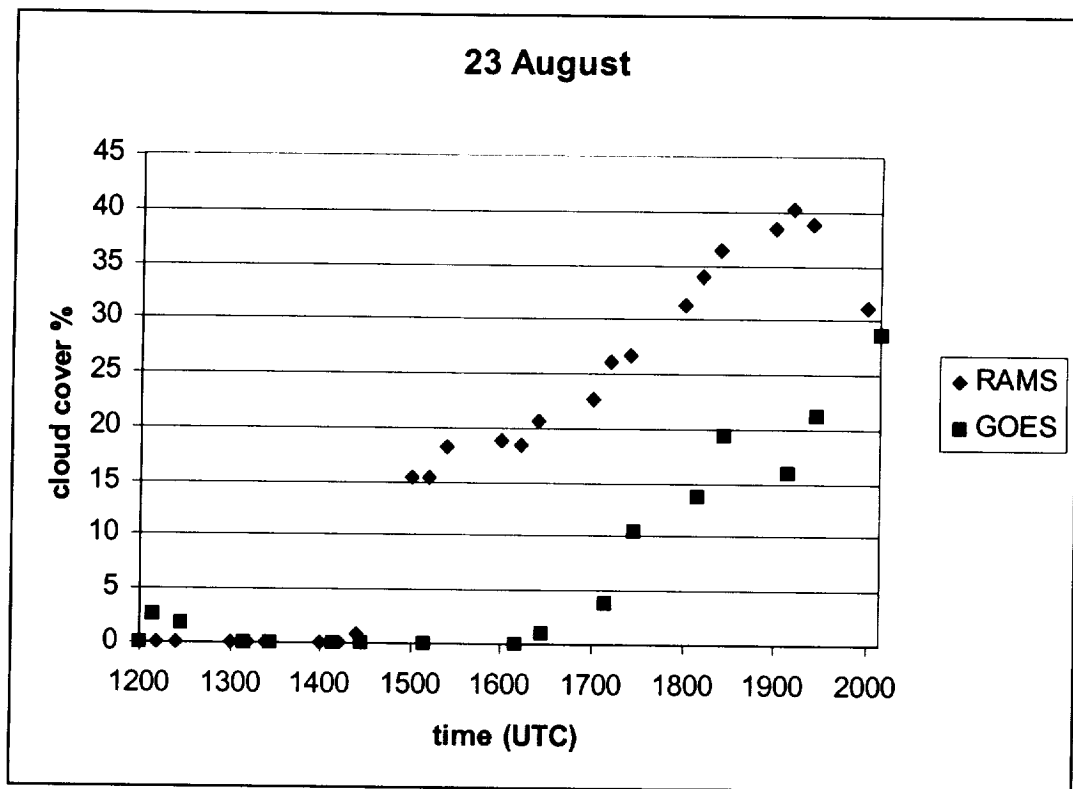


Figure 33c. Same as Fig. 33a but on 23 August 1996.

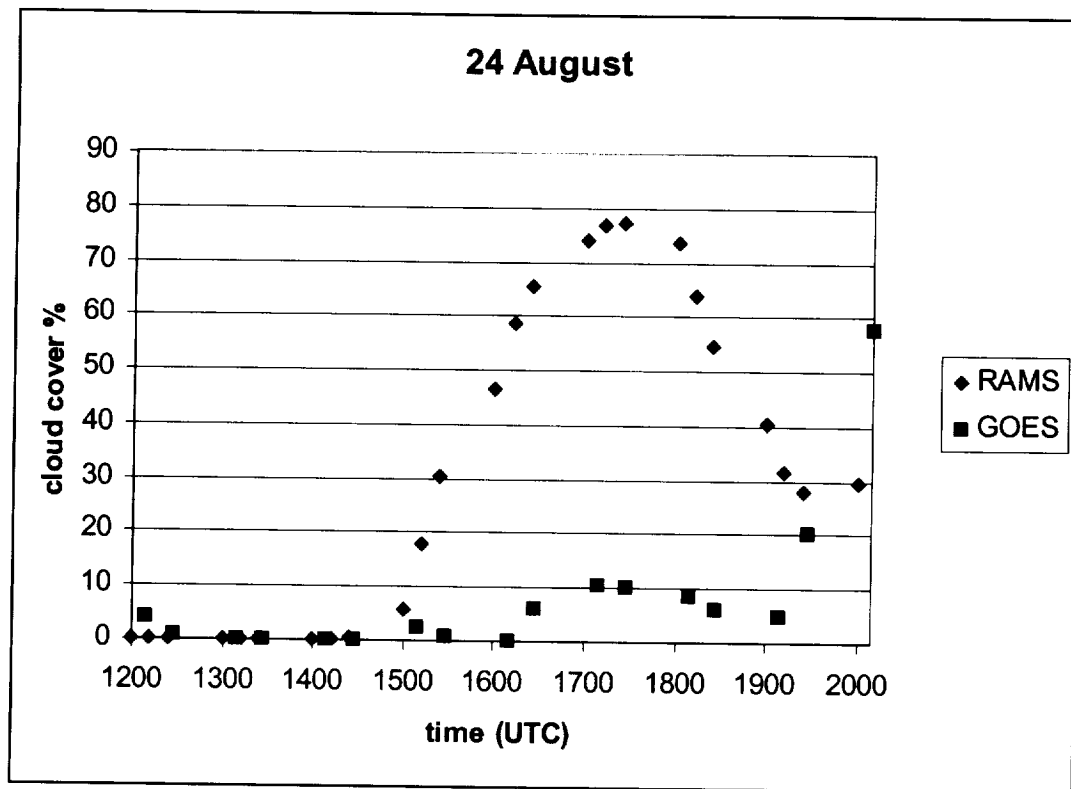


Figure 33d. Same as Fig. 33a but on 24 August 1996.

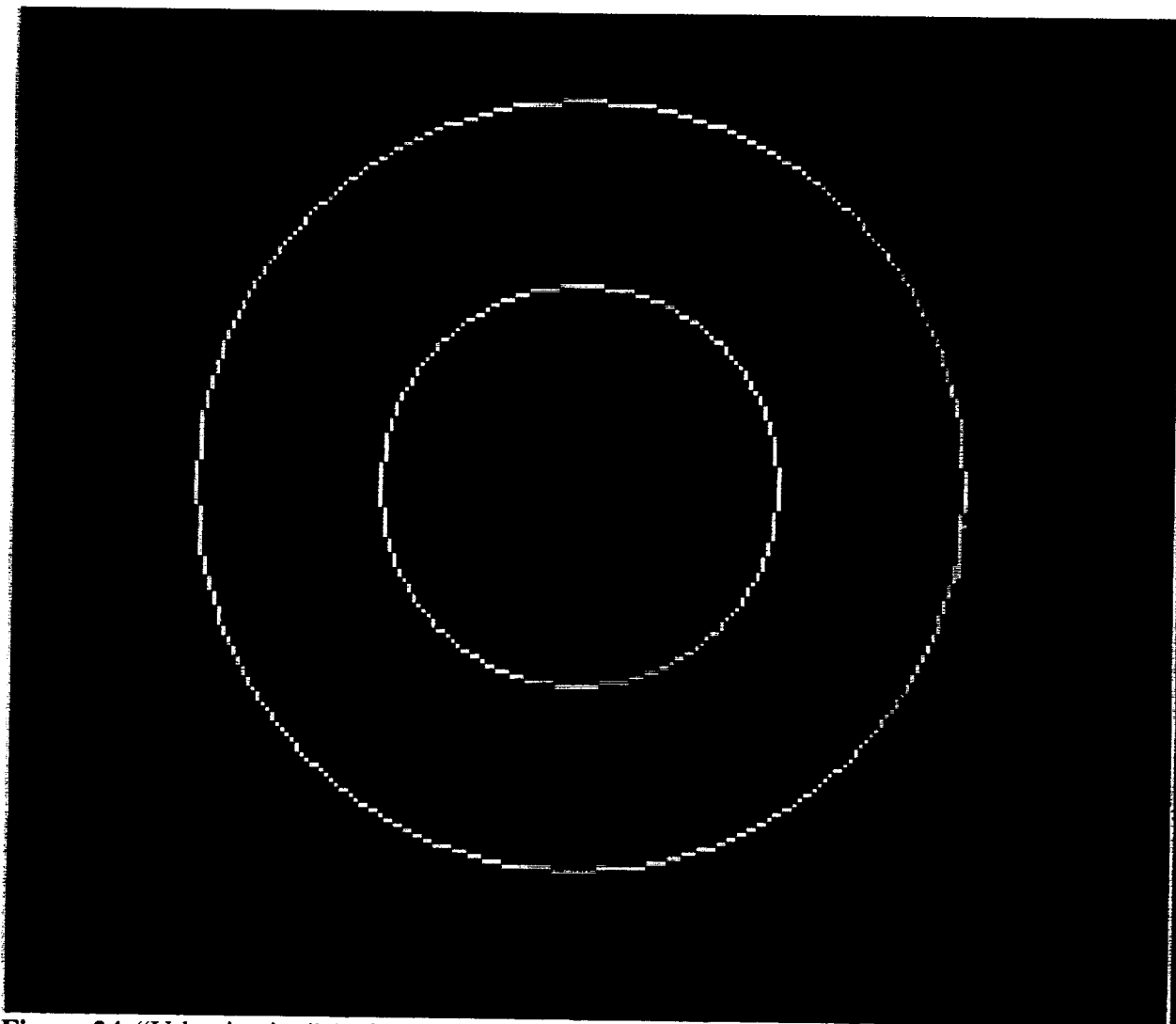


Figure 34. "Urbanization" (red) with mean cloud cover (green) at 1915 UTC on "clear" morning cases. Yellow areas are those which are both urban and cloud covered. The inner circle encloses the "urban" area for the next figure. The area between the two circles represents the surrounding "rural" area.

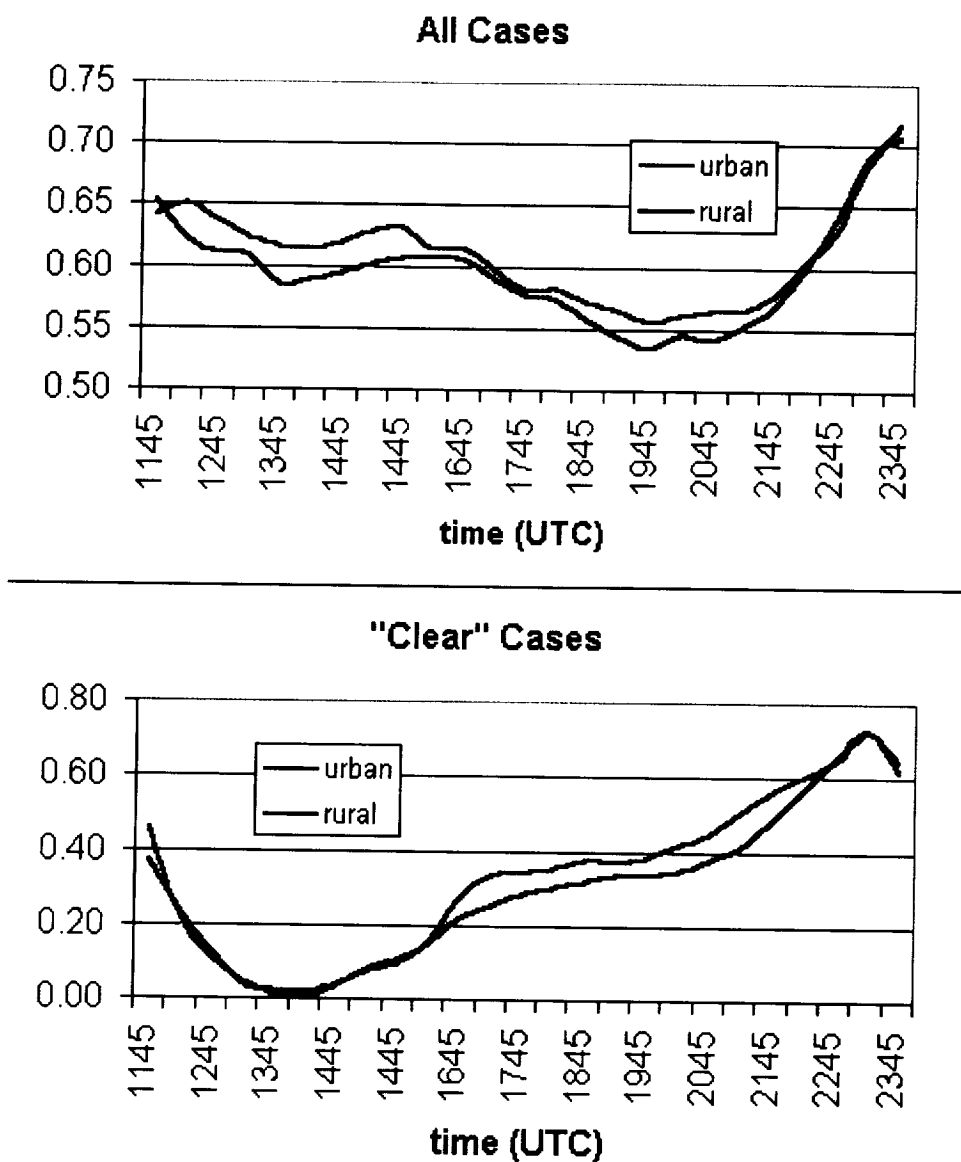


Figure 35. Fractional cloud cover in all cases (top) and clear morning cases (bottom). Except when it is clear, there are more clouds in the urban area than in the surrounding rural area.

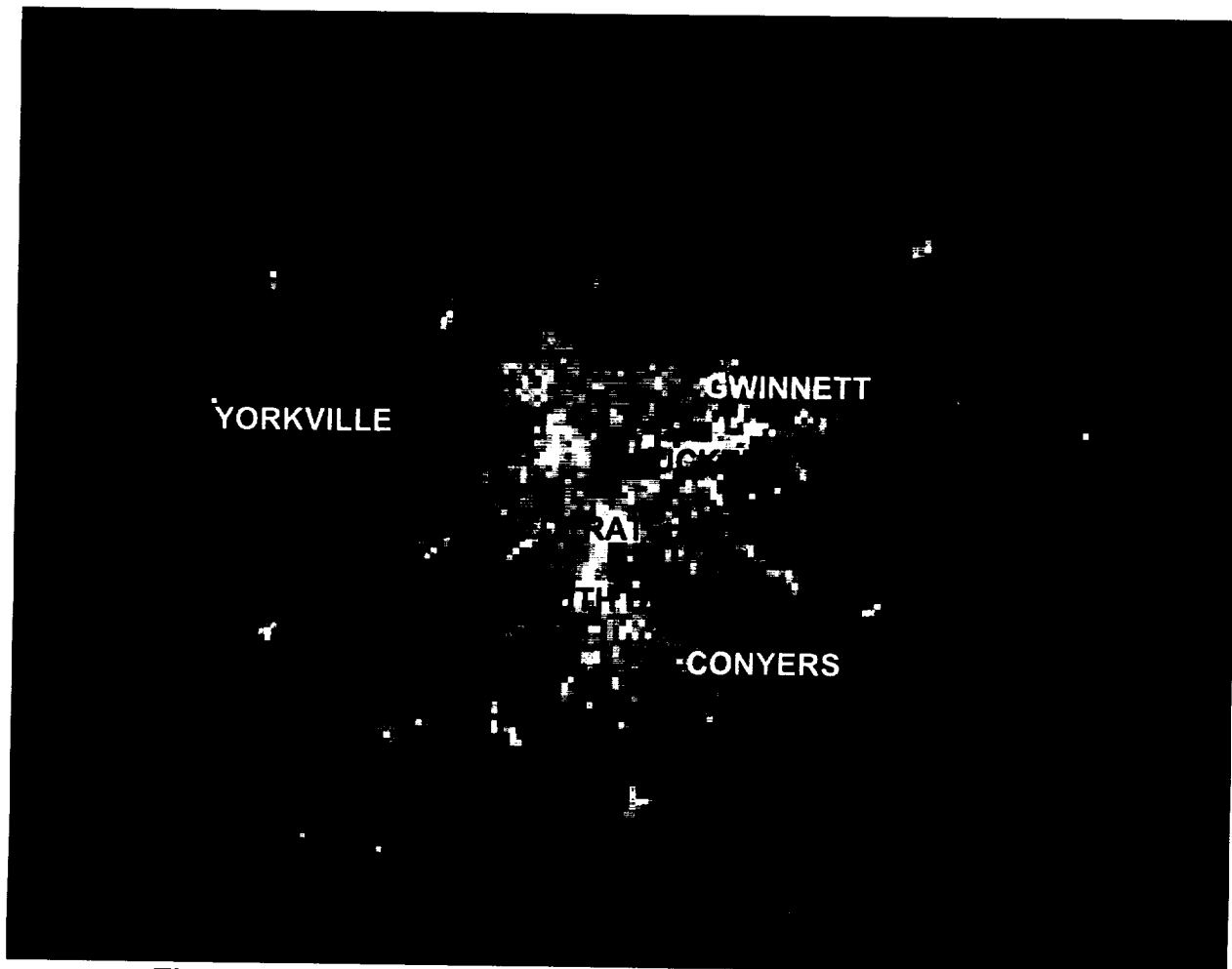


Figure 36. Location of air quality monitoring stations in and near Atlanta.

Correlation cloudiness vs. O3 concentration

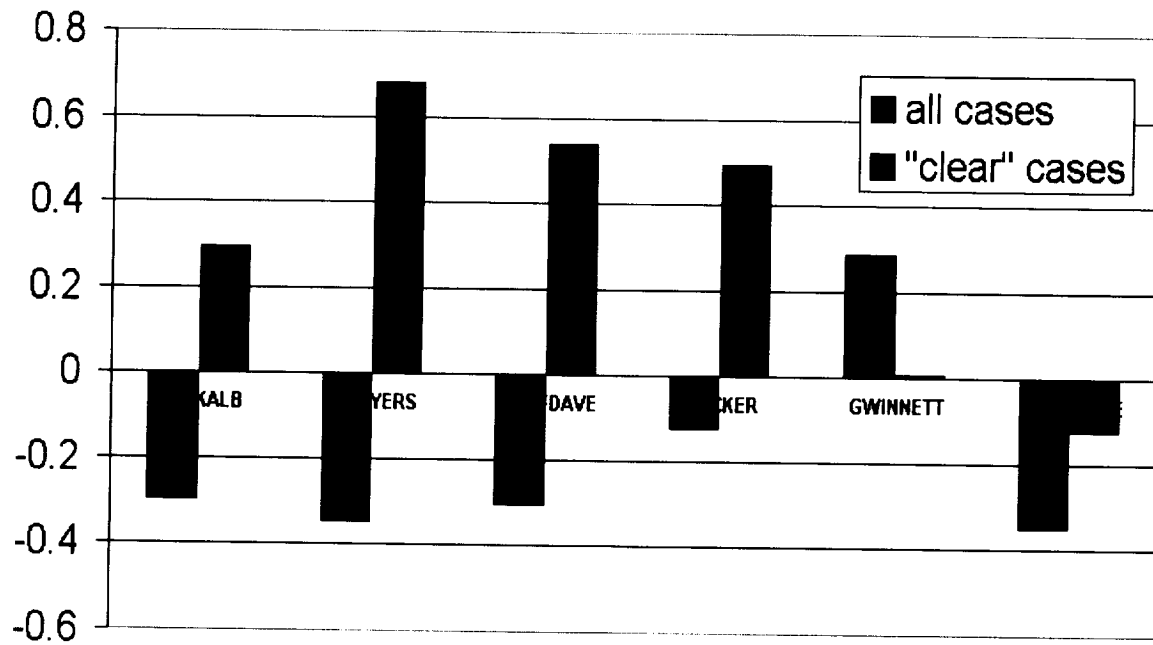


Figure 37. The correlation of cloudiness versus ozone concentration.

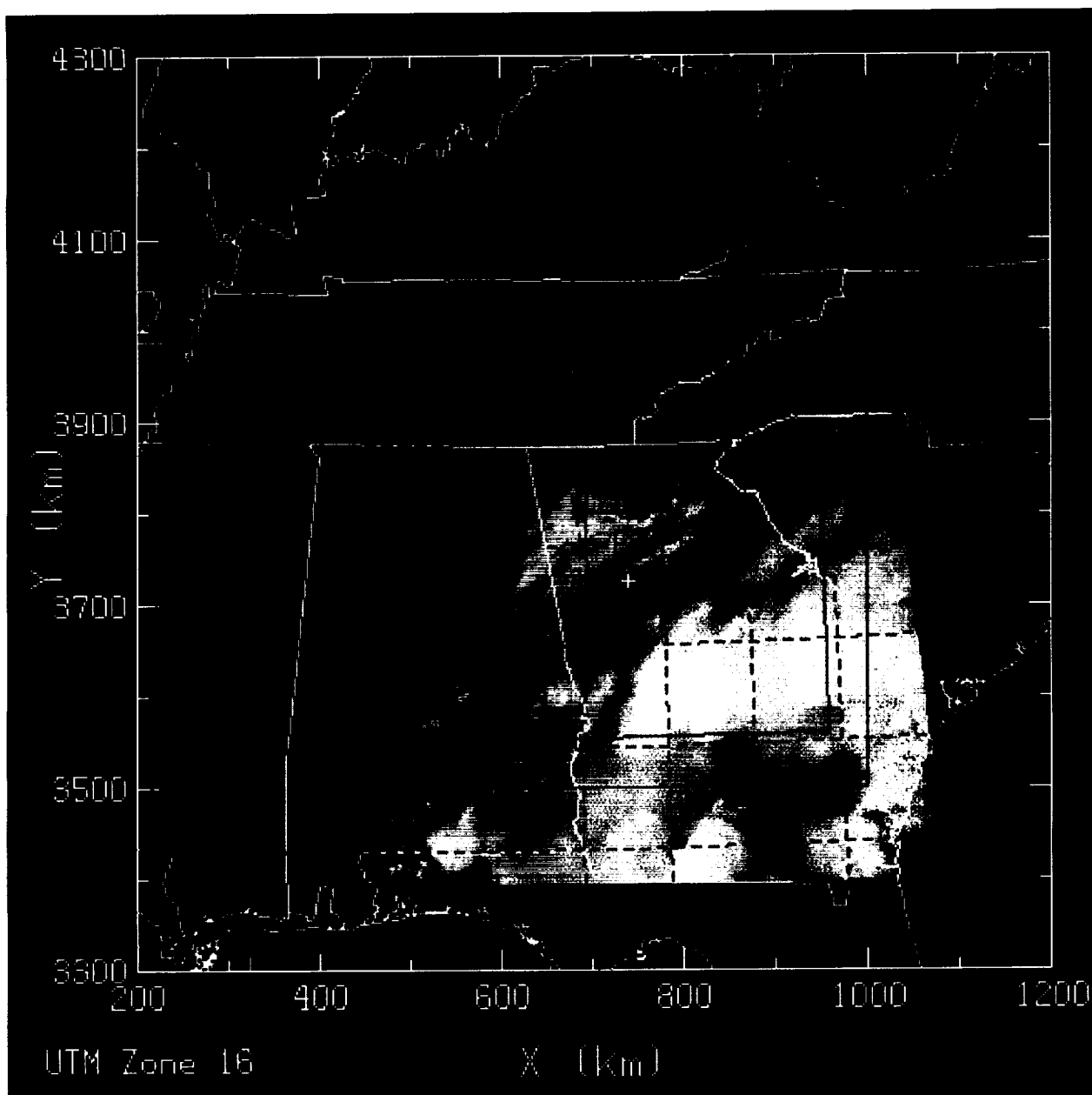


Figure 38. Experimental image showing a GOES visible image mapped into Universal Transverse Mercator (UTM) coordinates and overlaid with the three nested RAMS modeling grids (red).

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words) The goal of Project ATLANTA is to derive a better scientific understanding of how land cover changes associated with urbanization affect climate and air quality. In this project the role that clouds play in this relationship was studied. Through GOES satellite observations and RAMS modeling of the Atlanta area, we found that in Atlanta (1) clouds are more frequent than in the surrounding rural areas; (2) clouds cool the surface by shading and thus tend to counteract the warming effect of urbanization; (3) clouds reflect sunlight, which might otherwise be used to produce ozone; and (4) clouds decrease biogenic emission of ozone precursors, and they probably decrease ozone concentration. We also found that mesoscale modeling of clouds, especially of small, summertime clouds, needs to be improved and that coupled mesoscale and air quality models are needed to completely understand the mediating role that clouds play in the relationship between land use/land cover change and the climate and air quality of Atlanta. It is strongly recommended that more cities be studied to strengthen and extend these results.					
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